“Earth mantle dynamics from planetary perspective”

Water in terrestrial planets

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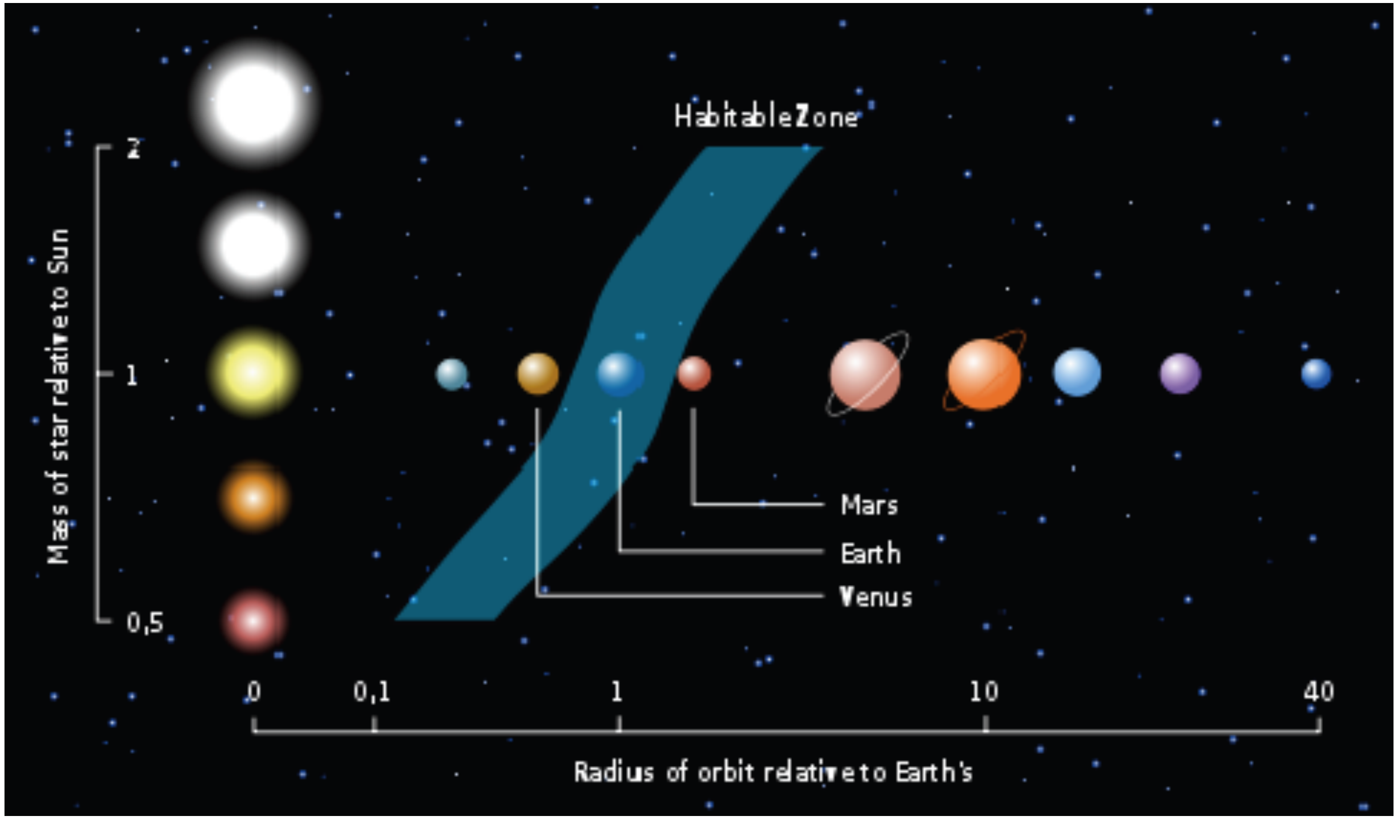
Outline

- Some background
  - Why water?
  - Processes controlling the water content of a planet
- Water in the **Moon**
  - Volatile acquisition during the later stage of planetary formation (giant impact)
- Water in **Earth**
  - Water distribution in Earth
  - Global water circulation and the stability of ocean mass
  - Plate tectonics on **terrestrial planets (super-Earths)**

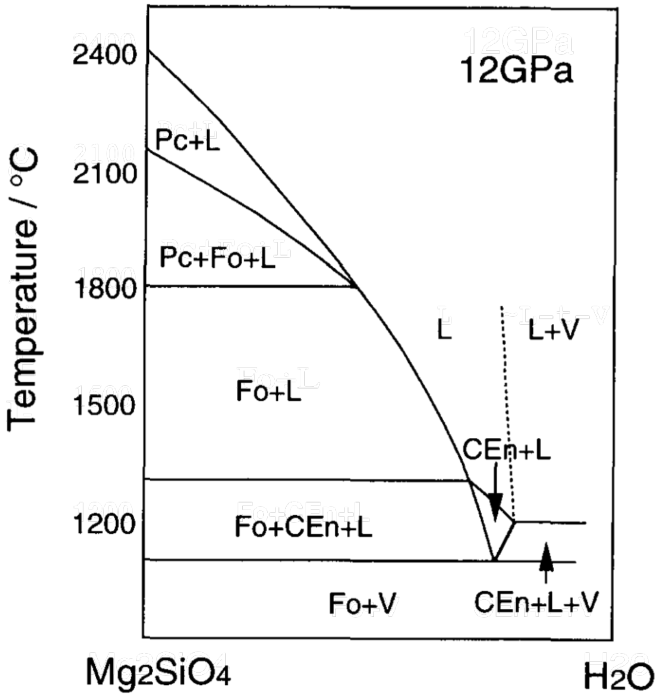
Why water?

life ←→ water (?) [“habitable zone”]



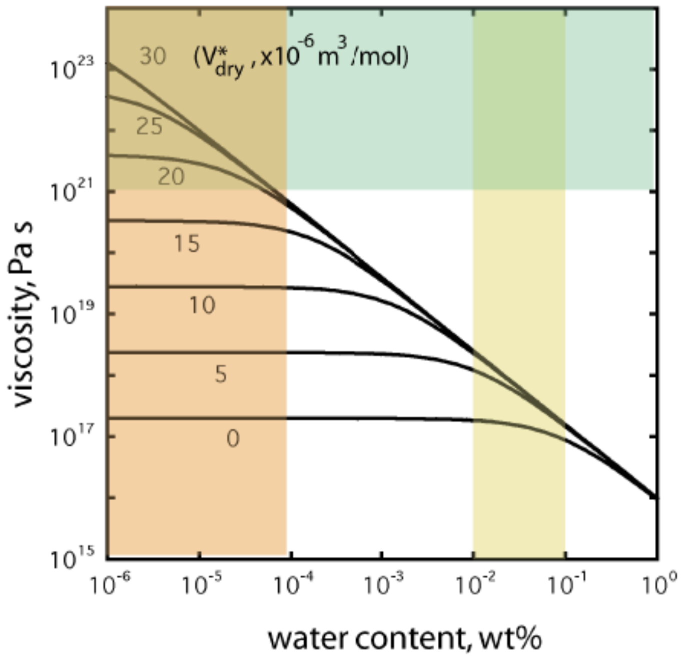
Water → melting, rheological properties → dynamics and evolution of terrestrial planets

melting



Inoue et al. (1994)

viscosity

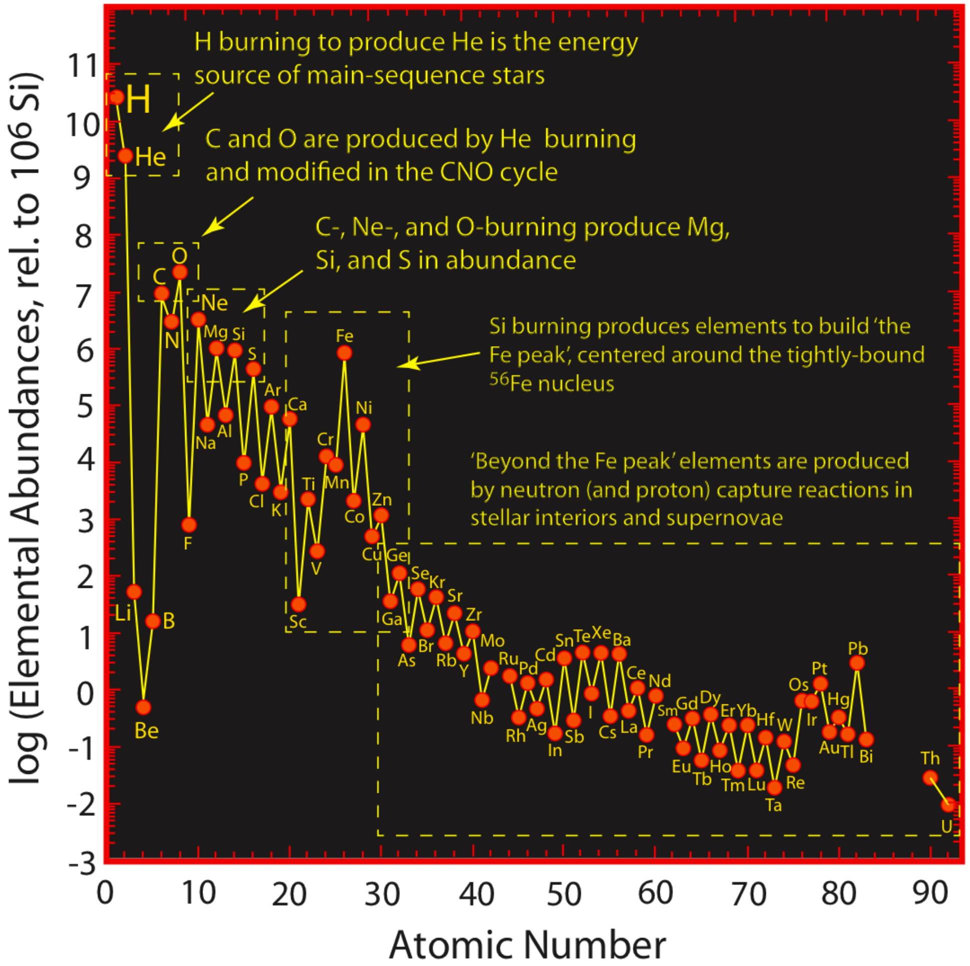


Karato (2010)

Processes controlling the water (volatiles) distribution in terrestrial planets

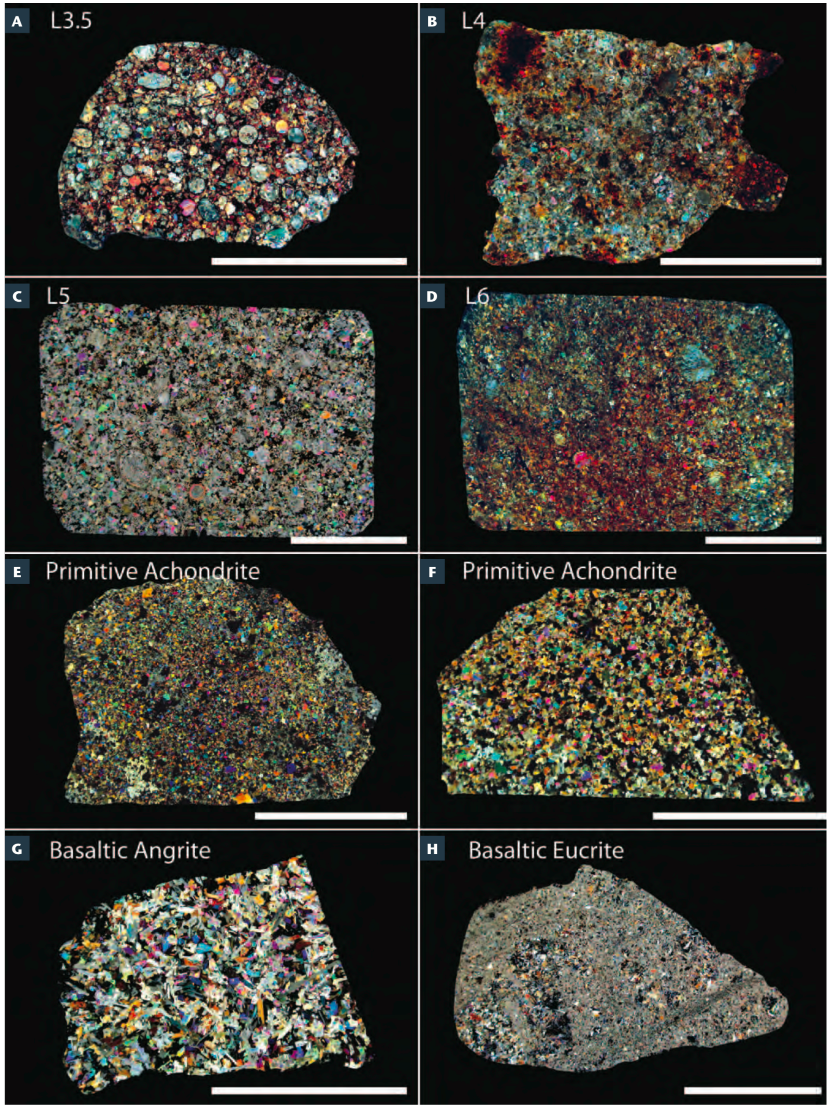
- **Condensation** of nebula
- **Collisions**, **magma ocean**: volatile loss?
- Magma ocean **solidification**, over-turn
- **Solid-state convection, plate tectonics**

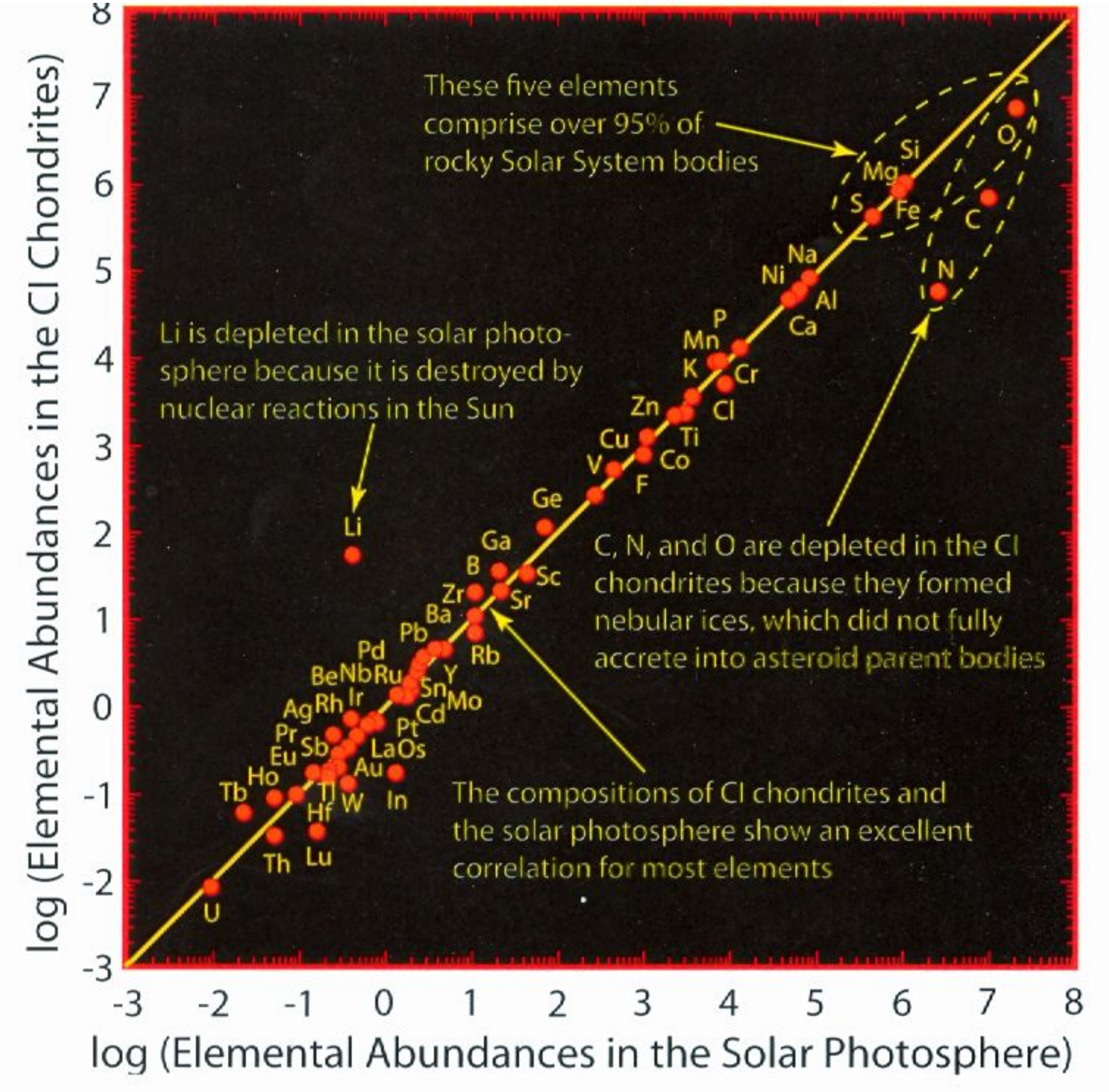
The solar system has a lot of volatiles.



Lauretta (2011)

meteorites ~ terrestrial planets



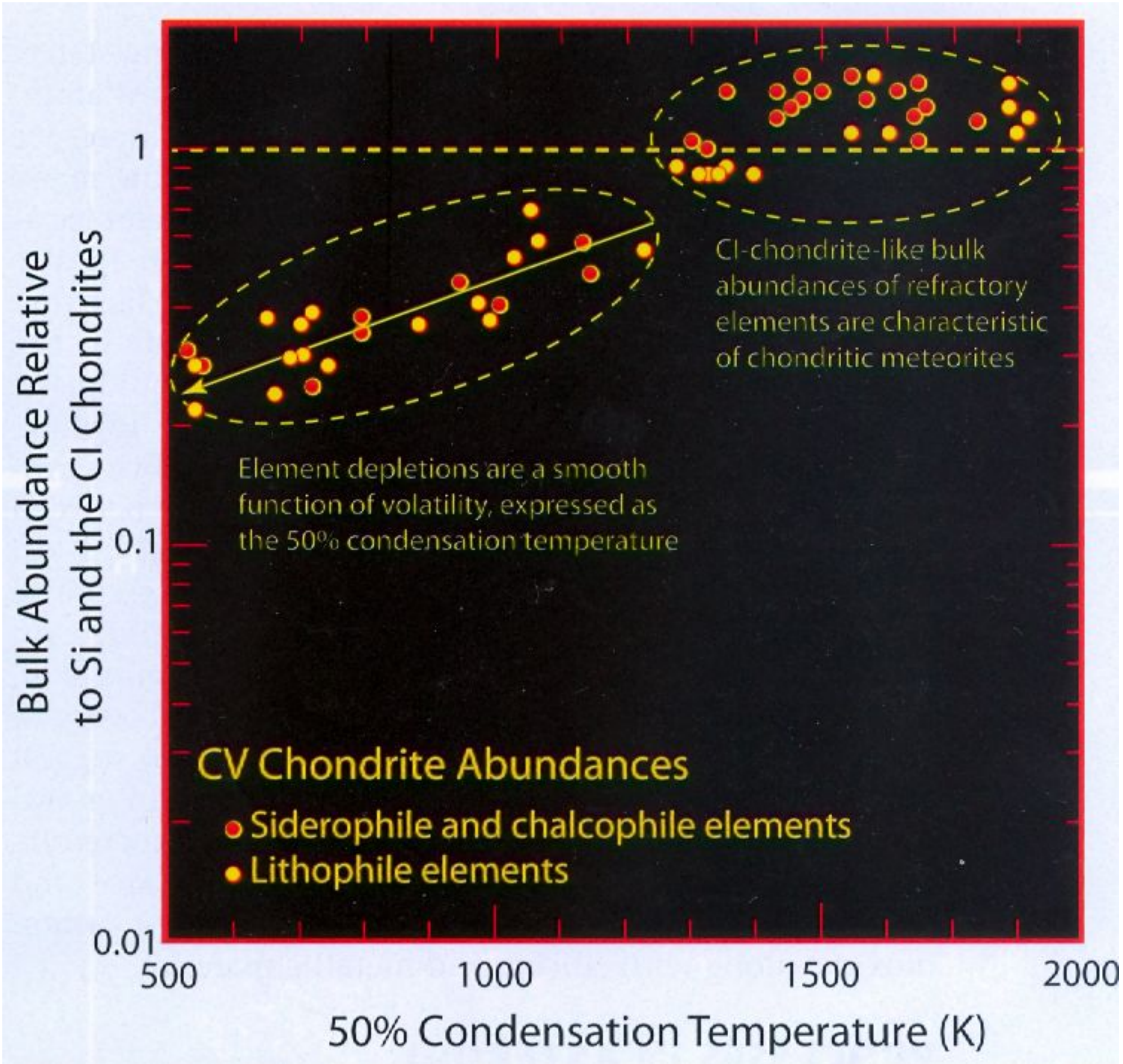


Harold Urey (1893-1981)

Lauretta (2011)

(terrestrial) planets ~ meteorite ~ solar abundance

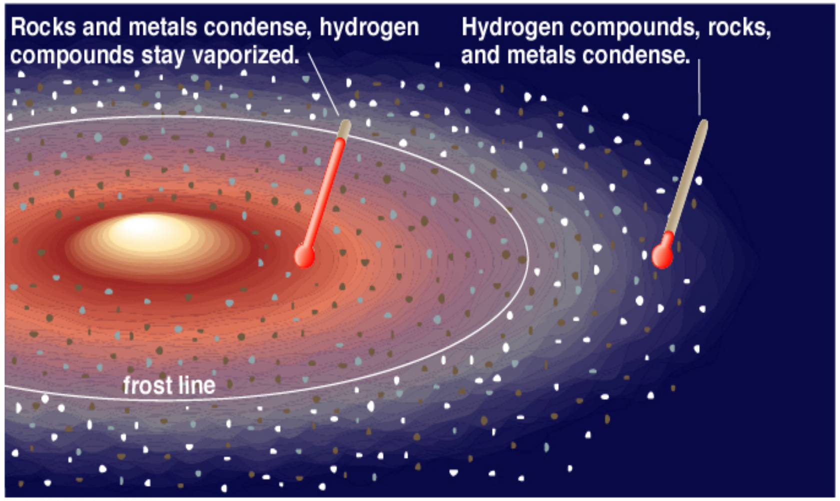
(except for volatile elements)

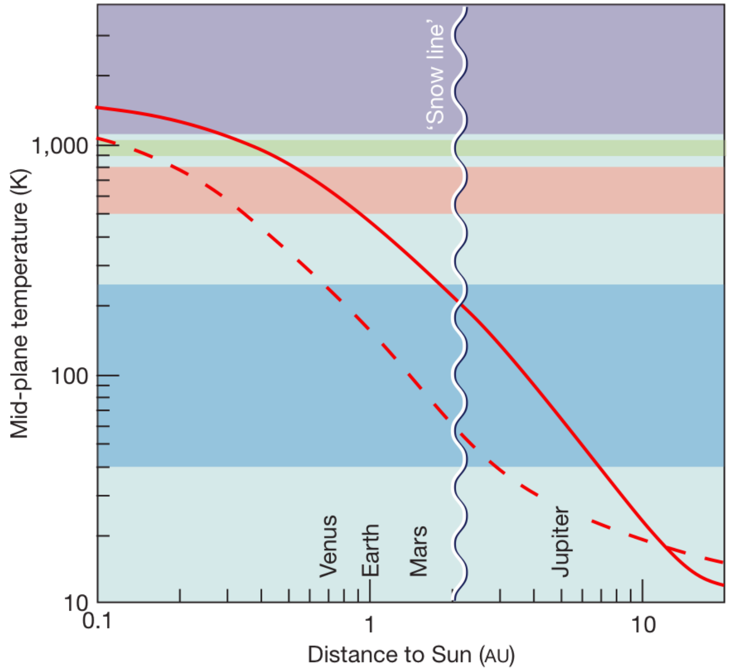


Lauretta (2011)

Meteorites (~planets) ~ solar abundance – volatiles (condensation)

Condensation in the solar nebula





Materials in the Solar Nebula

	Metals	Rocks	Hydrogen Compounds	Light Gases
Examples	iron, nickel, aluminum	silicates	water (H_2O) methane (CH_4) ammonia (NH_3)	hydrogen, helium
Typical Condensation Temperature	1,000–1,600 K	500–1,300 K	<150 K	(do not condense in nebula)
Relative Abundance (by mass)	(0.2%)	(0.4%)	(1.4%)	(98%)

Small rocky (volatile-poor) planets near the star

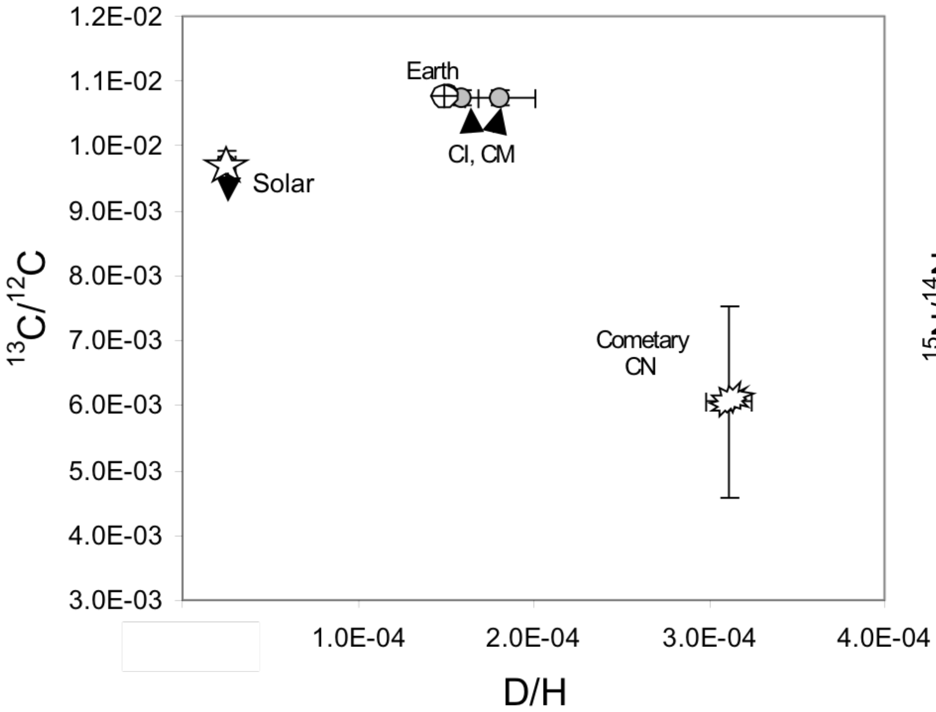
Large volatile-rich planets (giant planets) far away (beyond the "ice-line" ~2.7 AU)

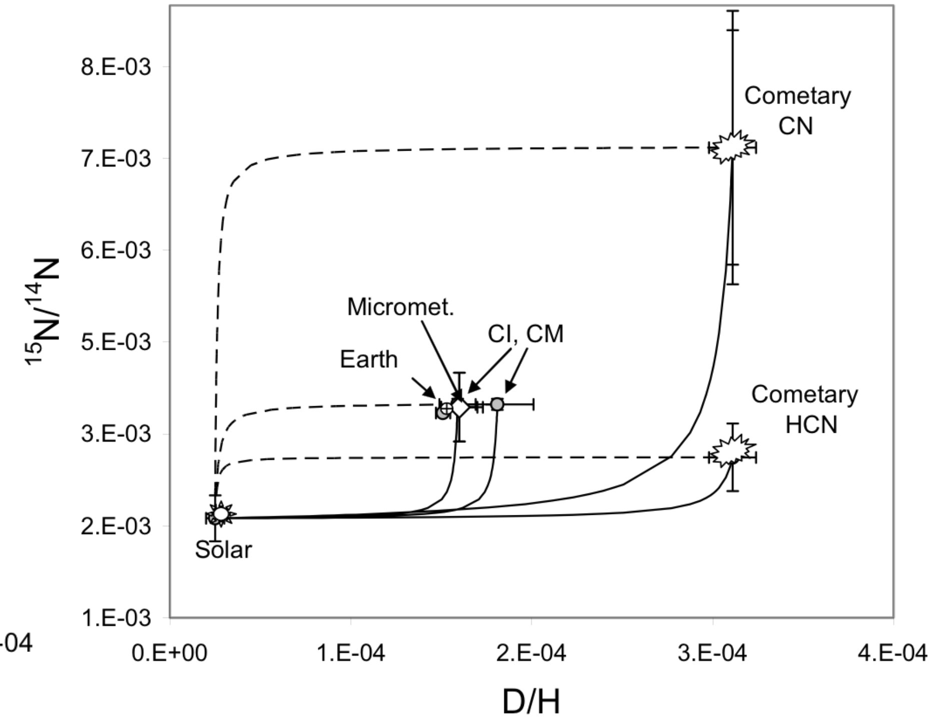
→Does this explain the volatile (water) content of Earth (rocky planets)?

Where did water come from?

comet: ~50%
carbonaceous chondrite: ~10%
ordinary chondrite: ~1 %
enstatite chondrite: <0.1 %

(note: continuous range of composition between carbonaceous-chondrite and comets, e.g., Gounelle, 2011)





Marty-Yokochi (2006)

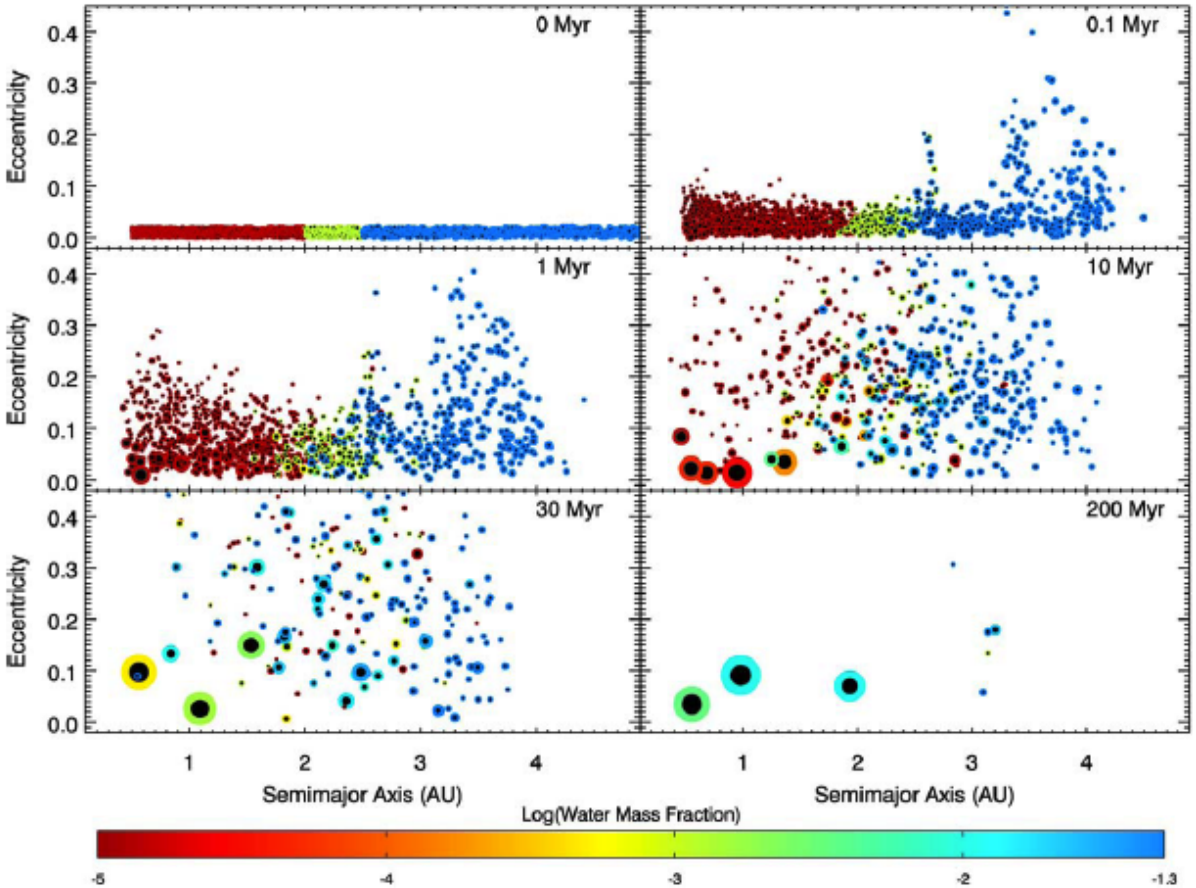
Isotopic observations (not only D/H but also C, N isotopes)

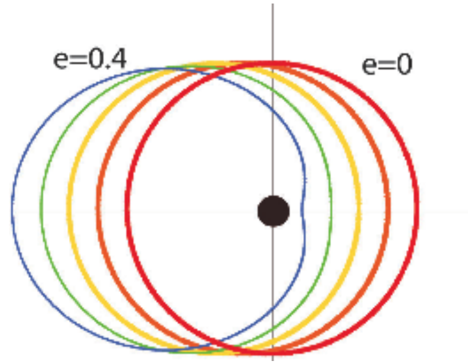
→ The main source of water on Earth is not comets but some materials similar to common meteorites.

→ **Did most of water-rich materials come from regions beyond the ice-line in the later stage of planetary accretion?**

A model of water delivery to growing planets

Most of water comes from regions beyond the "ice line" due to **orbital scattering** in the **later stage of accretion** (i.e., after core formation)
(see also Albarède, 2009)





Raymond et al. (2006) (Morbidelli et al., 2000)

- **Late or early volatile acquisition?**

  → different magma ocean evolution i.e, **mantle chemistry** (water affects the melting relationship).

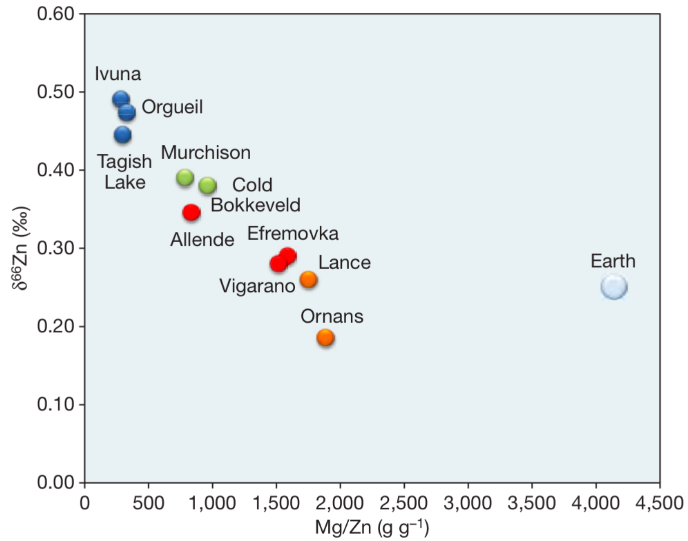
  → different **core chemistry** (volatiles in the core)

Albarède (2009)

Earth and chondrites are “depleted” (95% or more)

→ volatiles comes from material away from the “ice-line”

→ late stage volatile acquisition

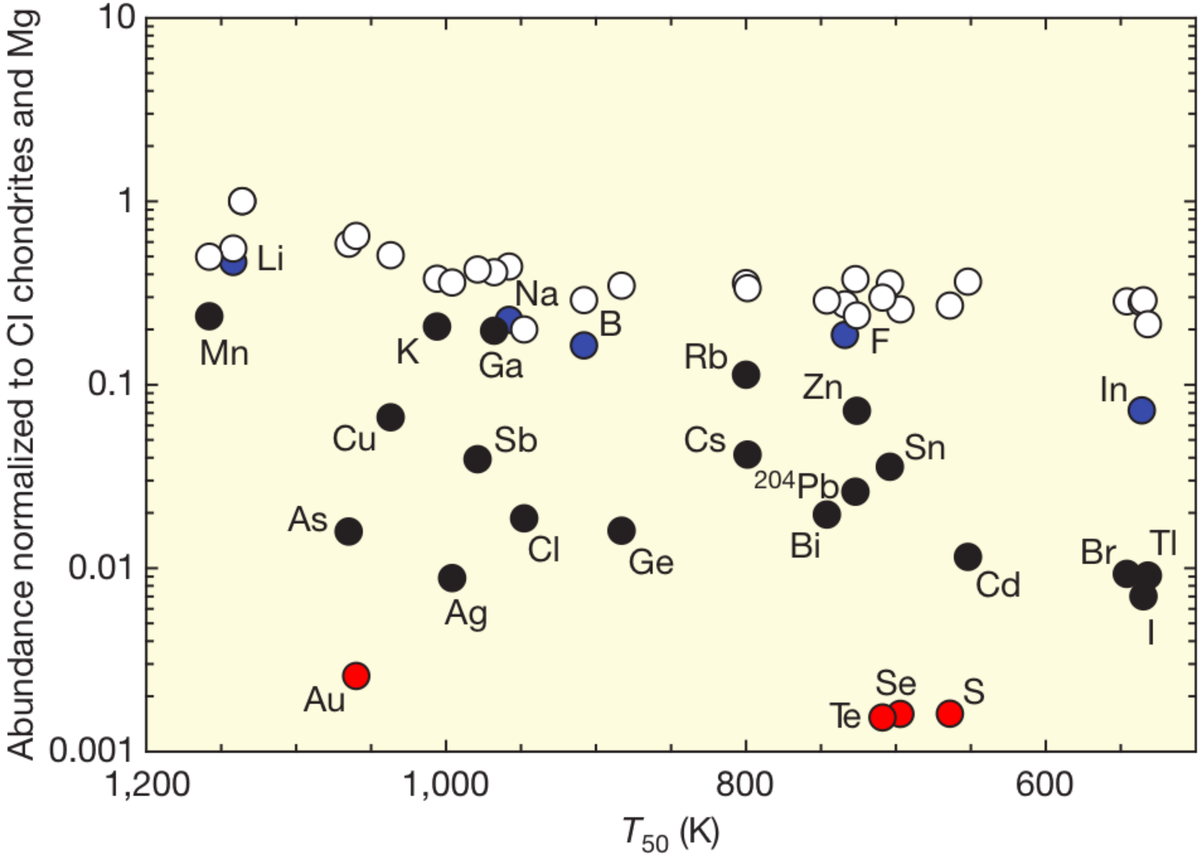


Albarède (2009)

- Earth = “wet” planet?
  - total mass = 6.0×10^{24} kg
  - ocean mass = 1.4×10^{21} kg
  - ocean/total = 0.023 %

→ **Not much water is needed to make “wet” Earth**

(99% depletion from CI chondrite → 0.1 %, i.e., ~40 ocean mass!)



Wood et al. (2010): discussions on Albarède (2009)

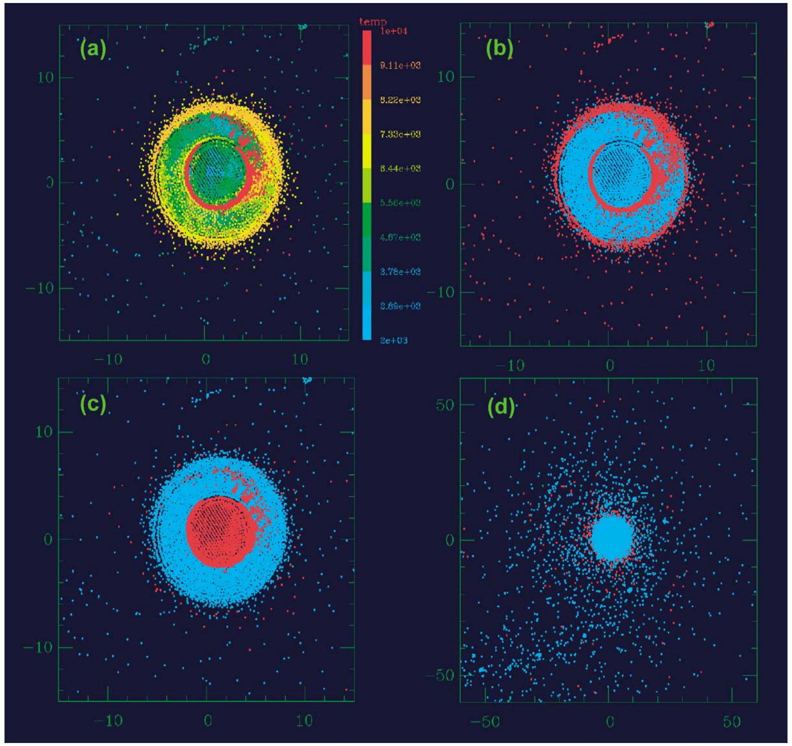
"Siderophile" and volatile elements are more depleted than other equally volatile but non-siderophile elements → **volatile acquisition before core formation** → **Hydrogen in the core?**

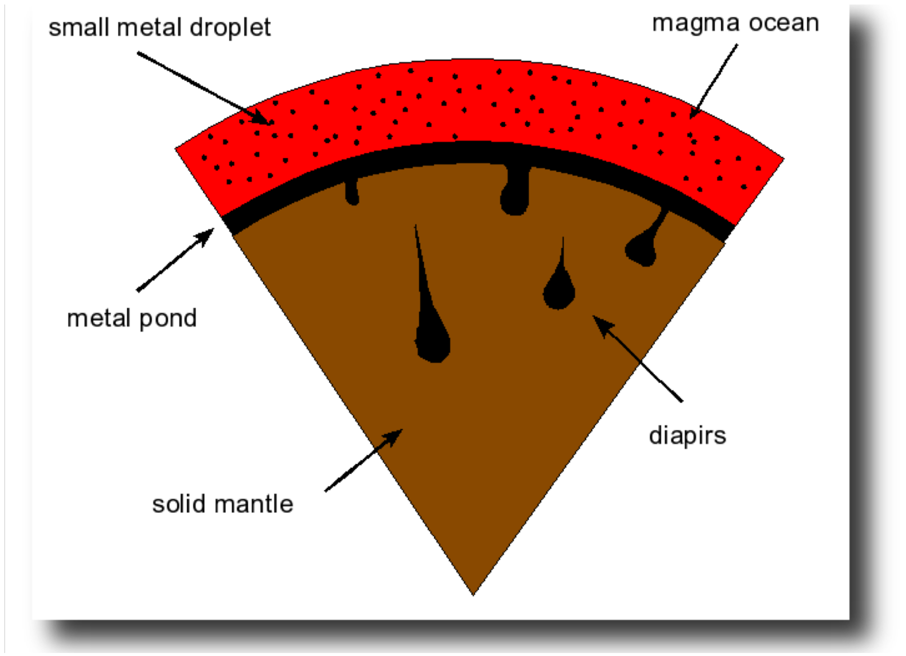
Volatile loss during **later-stage collisions** (giant impacts)?

Late stage collision

large degree of heating

→ **vapor-rich disk, magma ocean**

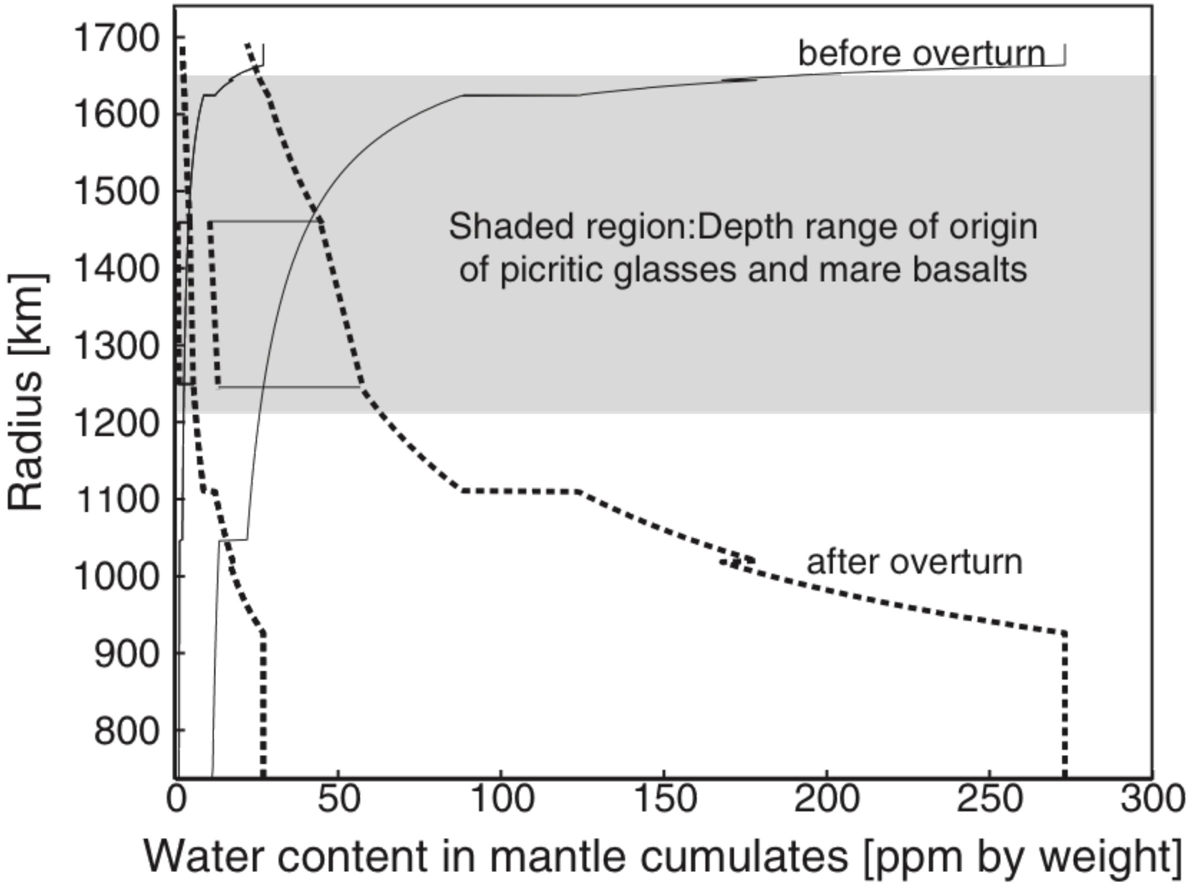




Canup (2004)

Water distribution after the solidification of magma ocean

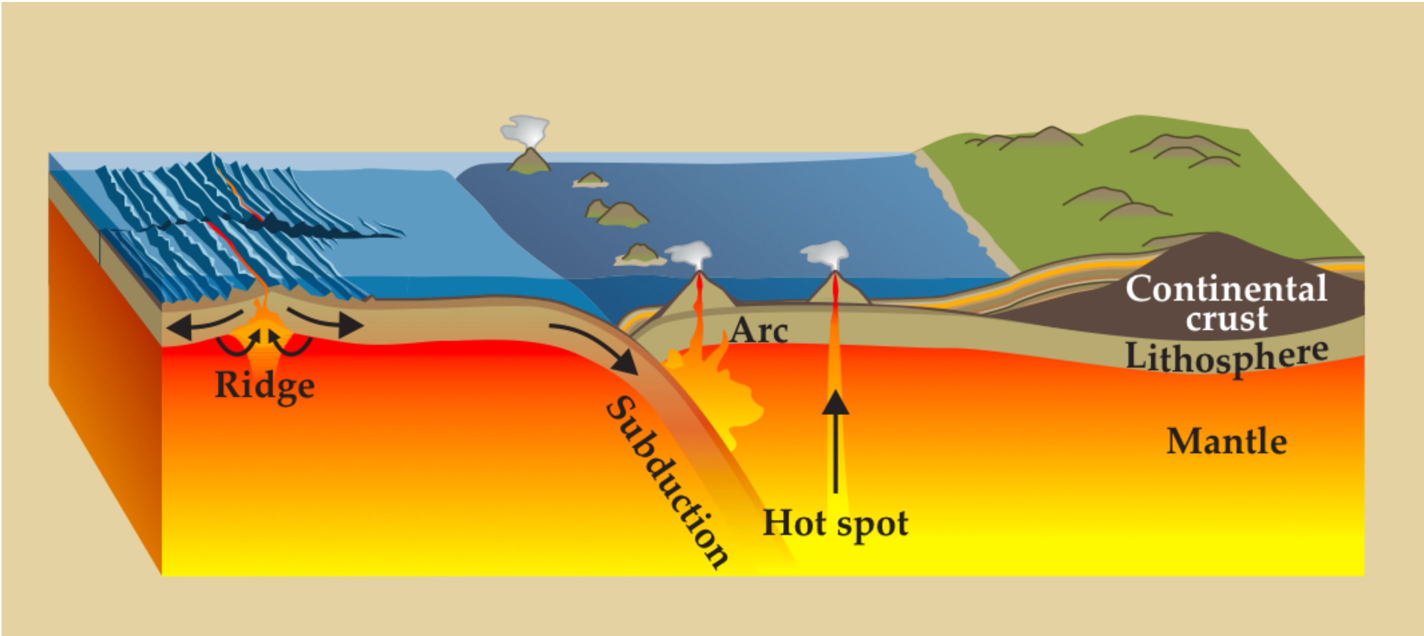
(Elkins-Tanton)



Moon

Evolution of ocean through geological history

global volatile circulation ← plate tectonics



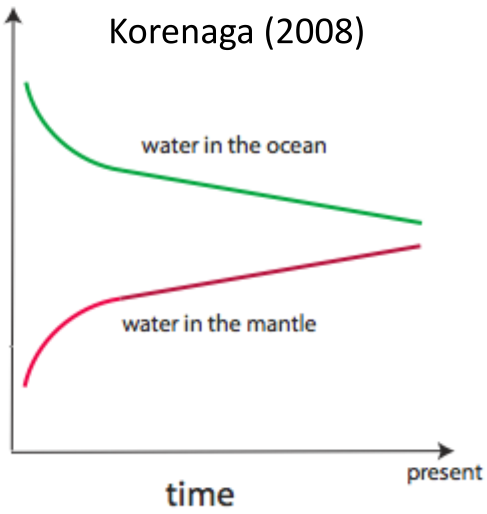
Volatiles came from the basic building bocks of Earth (planets).
→ Ocean has been formed through the global material circulation.

Hydrosphere-solid Earth interaction

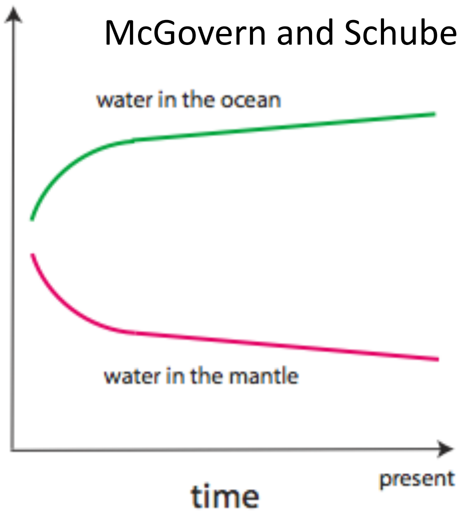
→ **Hydrosphere (ocean) has evolved through the interaction with the solid Earth.**

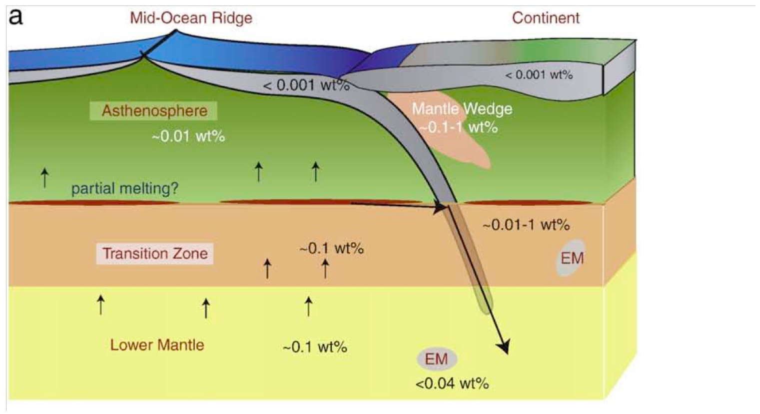
→ **But the nature of interaction is poorly understood.**

Korenaga (2008)



McGovern and Schubert (1989)





Karato (2011)

negative feedback (stable water content) or positive feedback?

rheology ←→ water (for deep mantle minerals)

Processes inside of the mantle: buffering water content (deep mantle melting)?

Water distribution in the mantle

Water in the Moon

How does a **giant impact** affect the volatile acquisition?

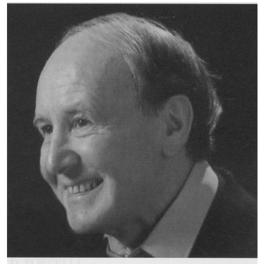
- Evidence of water in the Moon
  - Geochemical evidence
  - Geophysical evidence
- Processes of Moon formation and volatiles
  - Physical conditions of a proto-lunar disk
  - Phase diagram of silicate

Outline

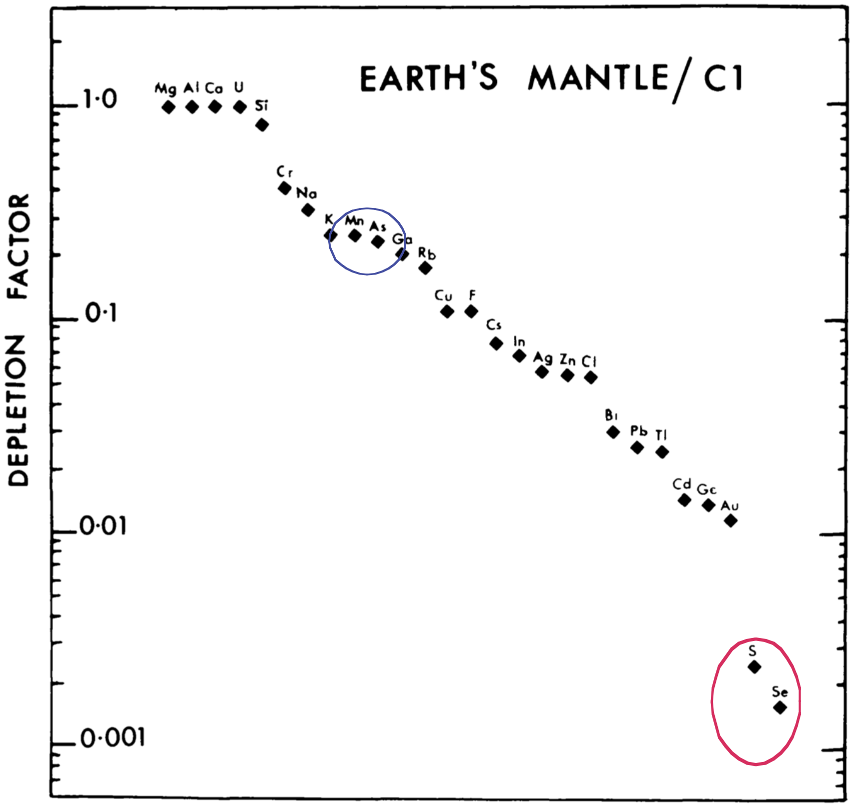
- "Wet" (not-so-dry) Moon?
  - Geochemical evidence
  - **Geophysical evidence**
    - **Electrical conductivity**
    - **Q (tidal dissipation)**
- Can we reconcile "wet" Moon with a giant impact model?
  - How does a planet get volatiles during condensation/accretion?
  - Giant impact and the fate of volatiles
    - **Importance of liquid phases**

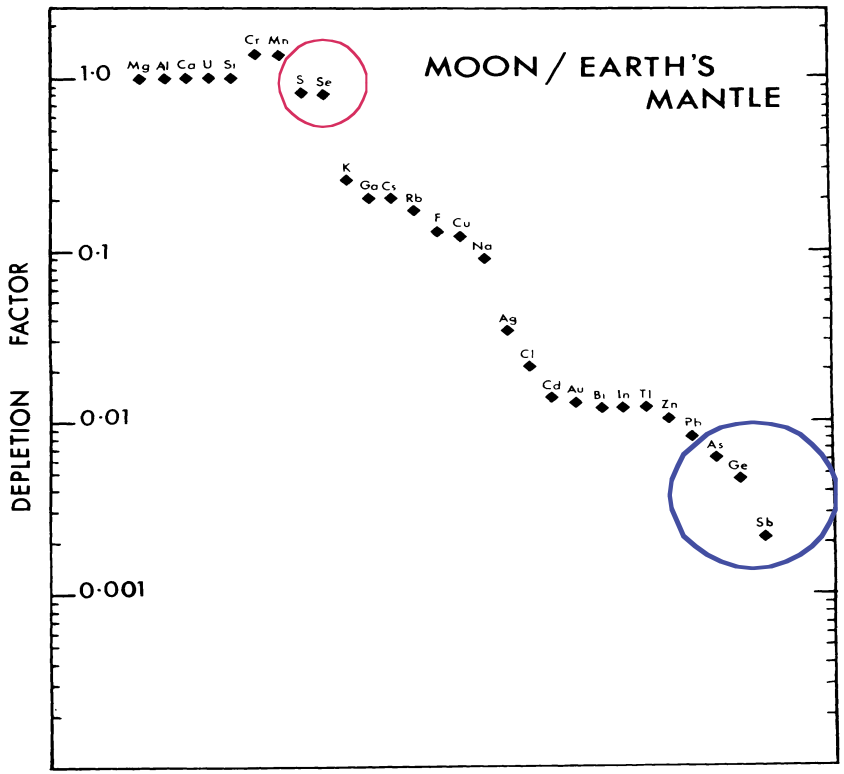
"dry" Moon

Ringwood-Kessen (1977)



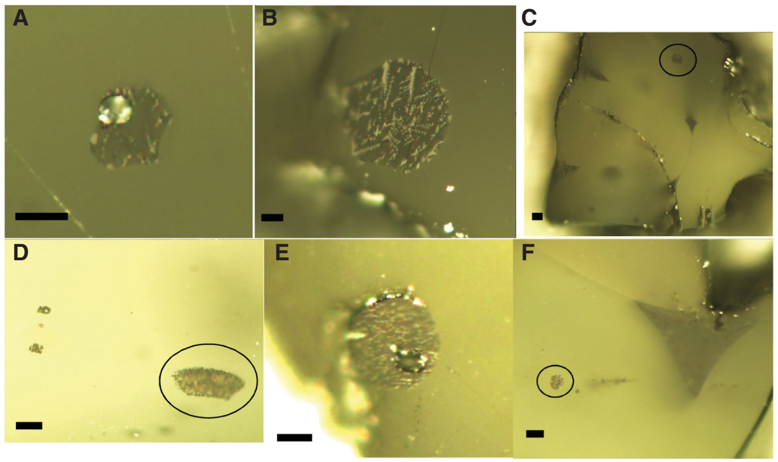
Ted Ringwood (1930-1993)



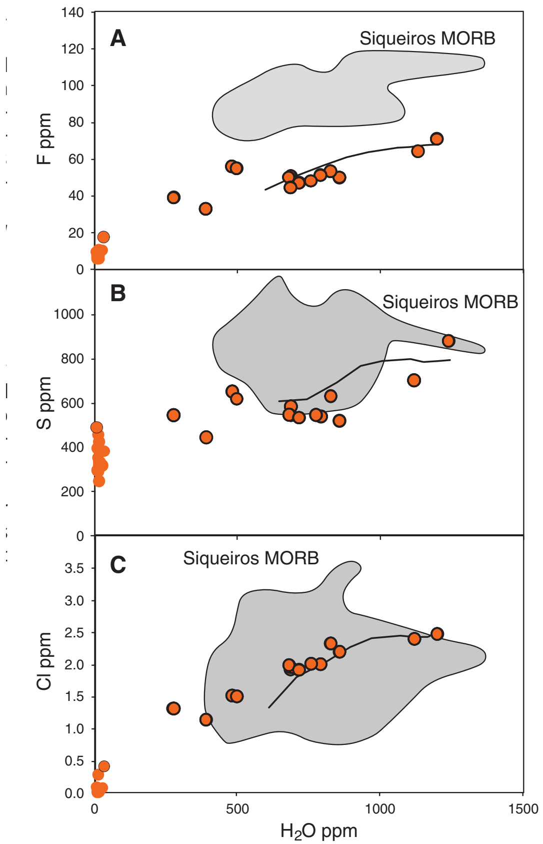


The Moon is more depleted than Earth.
Patterns of volatile loss for Earth and the Moon are different. → Volatile loss in the Moon in the **hydrogen and iron poor environment** (compared to the solar nebula)

Geochemical evidence for the "wet" Moon



(Hauri et al., 2011)



~0.01 wt% of water in the "source region" (similar to the asthenosphere on Earth) → **Where is water? Water in the deep interior?**

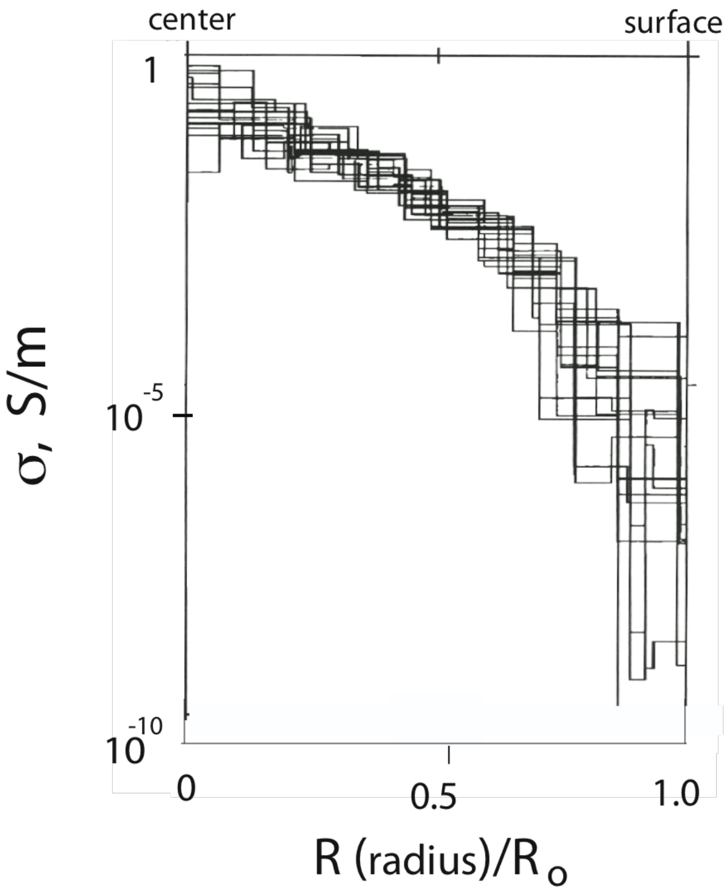
Geophysical approach

- Geophysical approach: spatial (depth) distribution of water

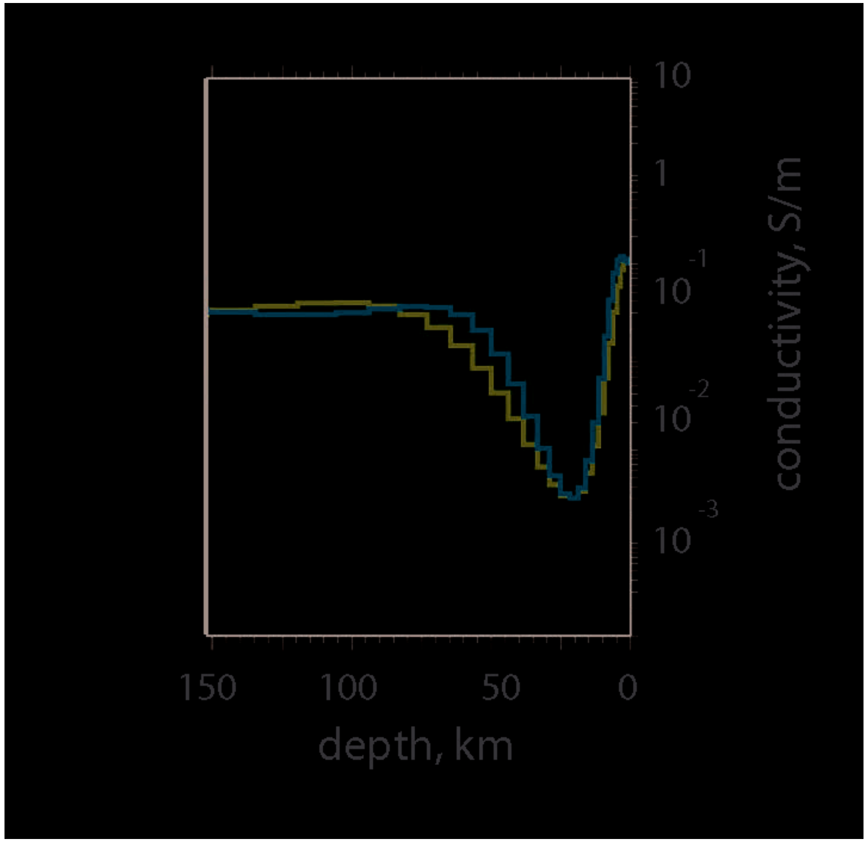
    (deep mantle)

- Water sensitive geophysical observations
  - Electrical conductivity
  - Seismic wave attenuation, tidal dissipation

Geophysical inference I:
electrical conductivity



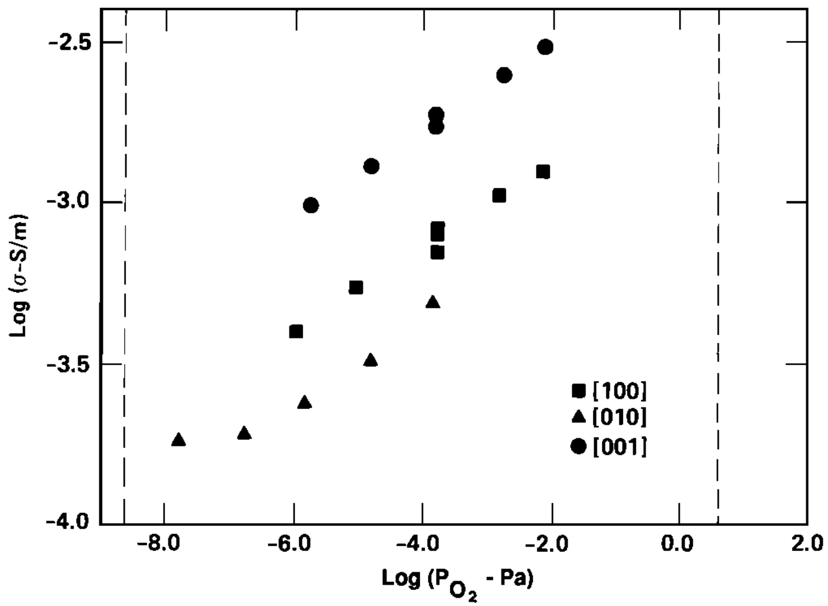
the Moon
(Hood et al., 1982)



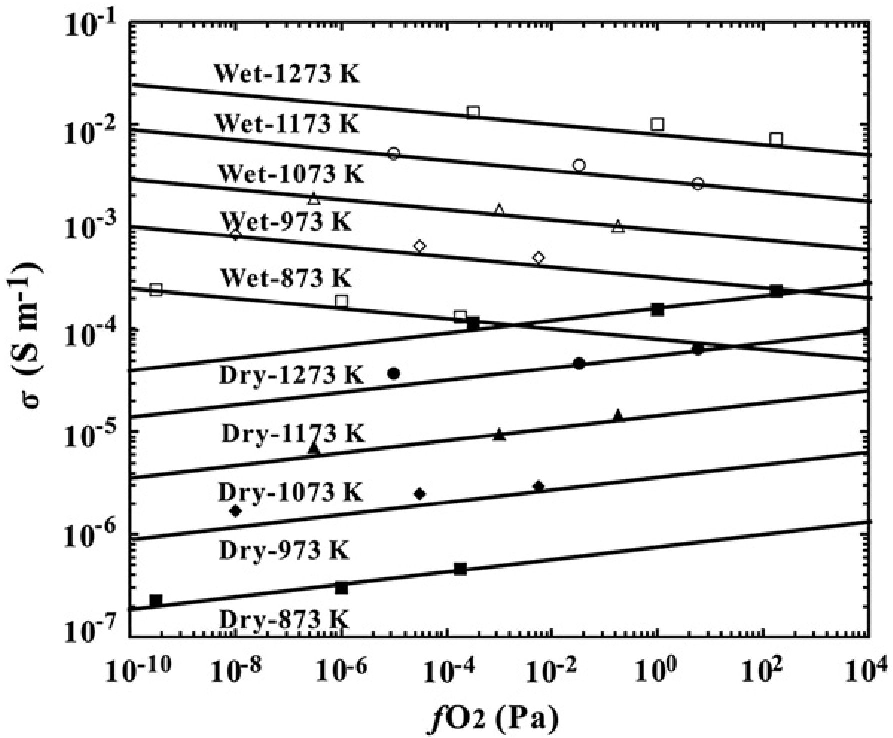
Earth's upper mantle
(Philippine Sea)
(Baba et al., 2012)

Does “dry” model work?

“dry” olivine (ortopyroxene) conductivity: T-fO2 dependent

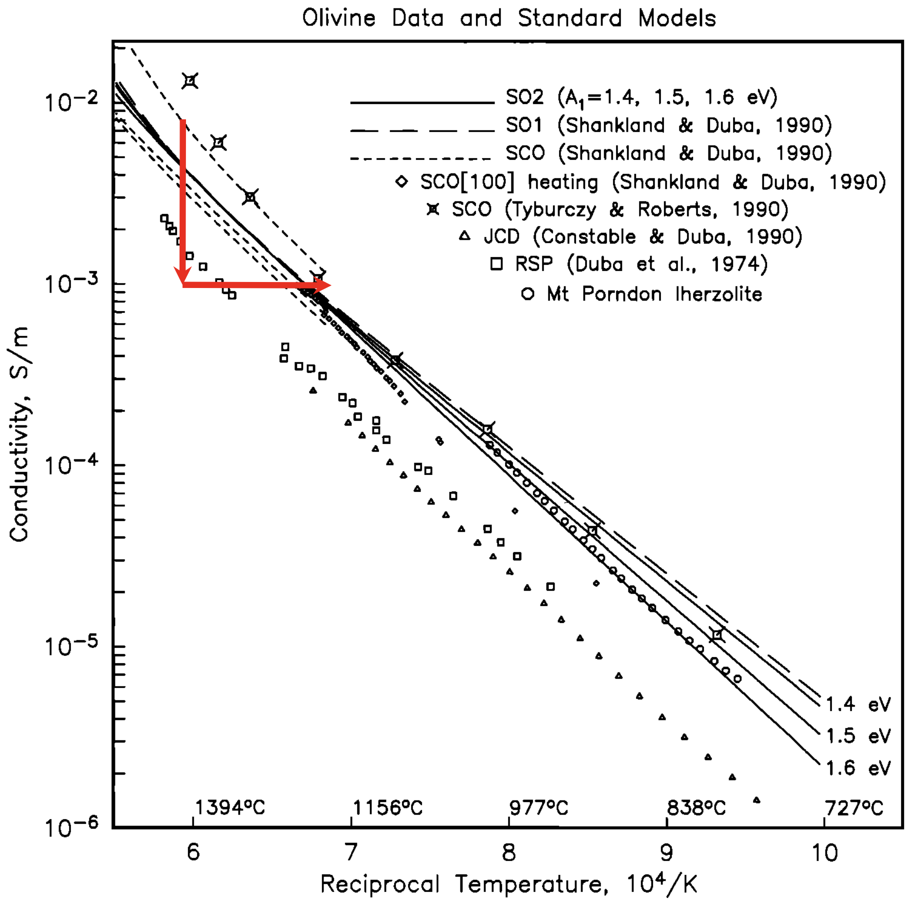


olivine



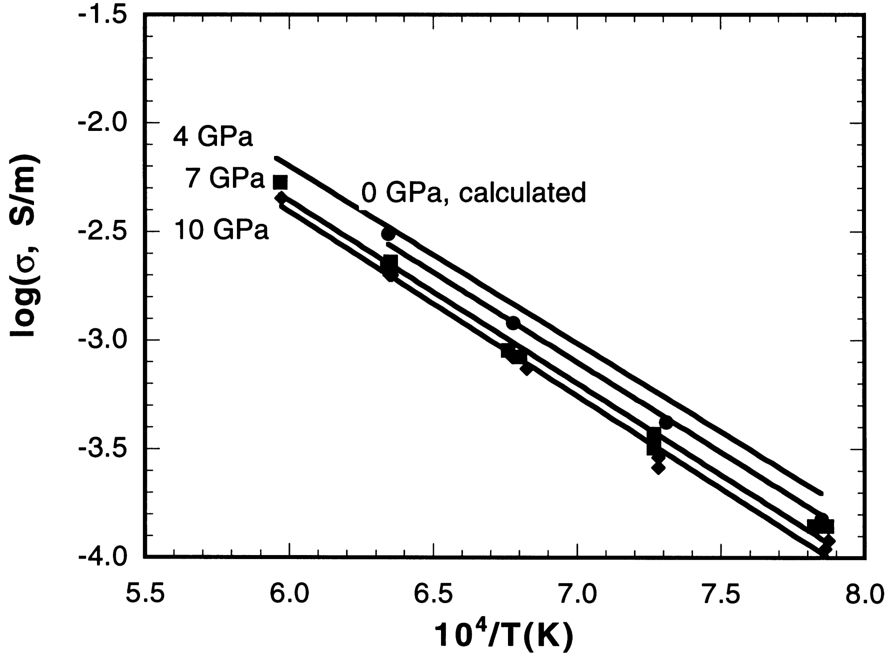
wadsleyite

Conductivity of "dry" olivine

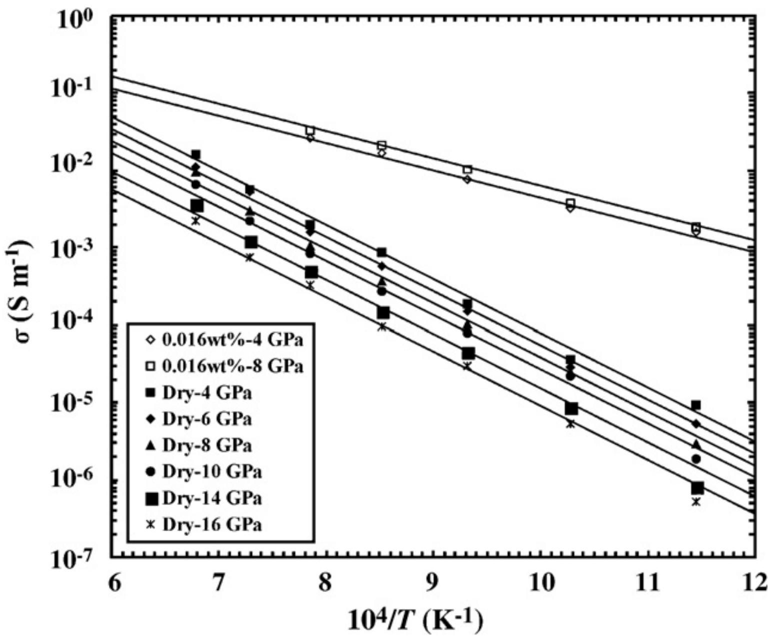


fO2 effect is important in the Moon (ΔT ~300 K)

Pressure effects are small

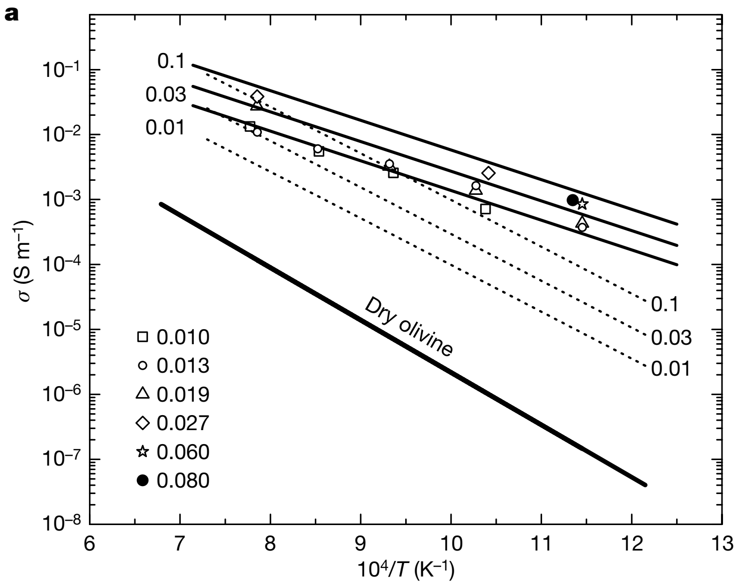


olivine (Xu et al., 2000)

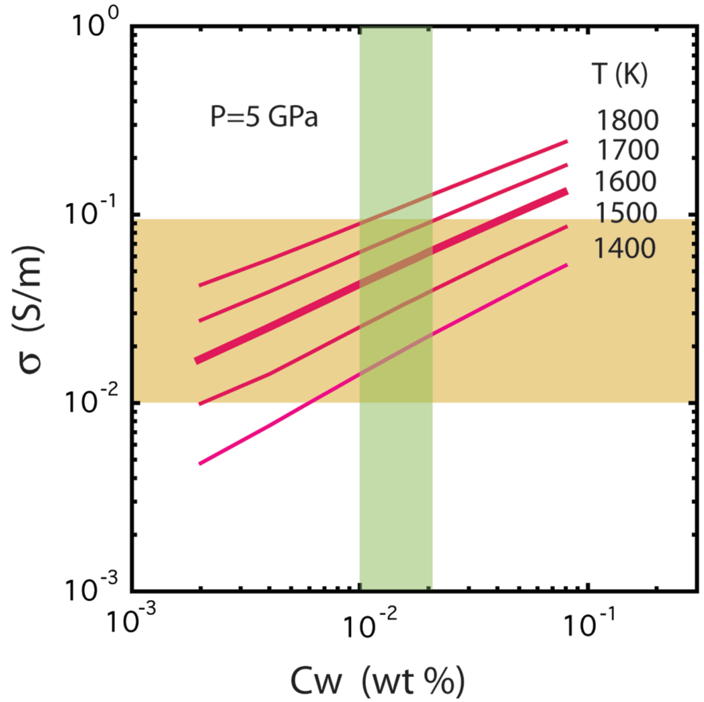


pyrope (Dai and Karato., 2009)

Water effect is large

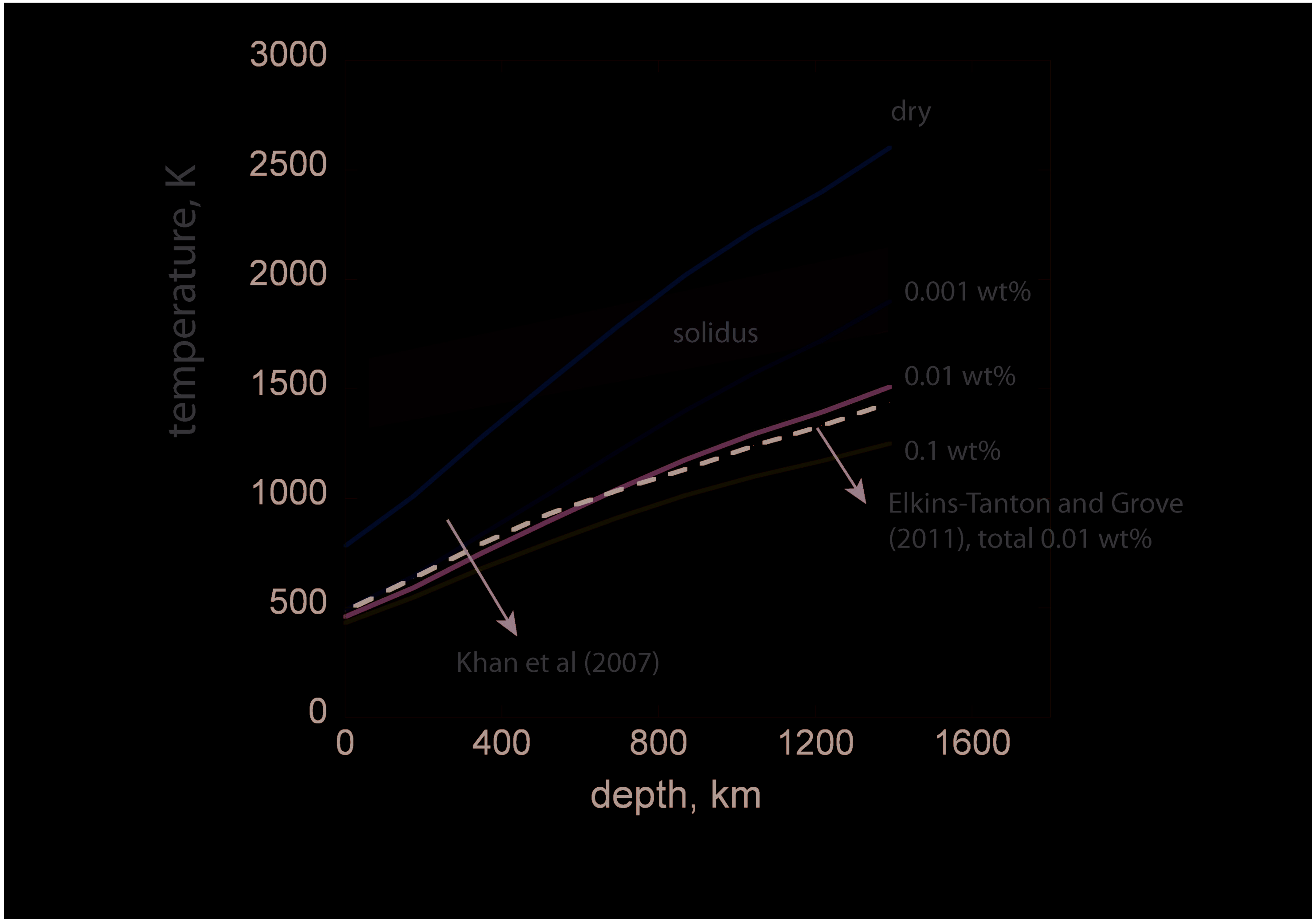


Wang et al., (2006)



Dai and Karato (2009)

Seleo-therms



→ The Moons deep mantle cannot be dry.

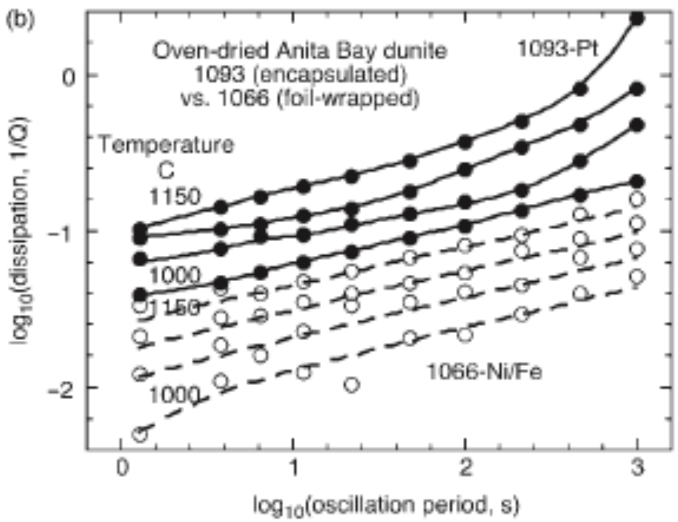
→ ~0.01 wt% of water provides a reasonable T-z.

Geophysical inference II: Q

$$Q^{-1} \sim (\omega\tau)^{-\alpha} \propto \tau^{-\alpha}$$

$\tau \propto \eta \propto \frac{1}{C_W^r}$ (for most cases), C_W : water content

$$\rightarrow \quad Q^{-1} \propto C_W^{\alpha r}$$

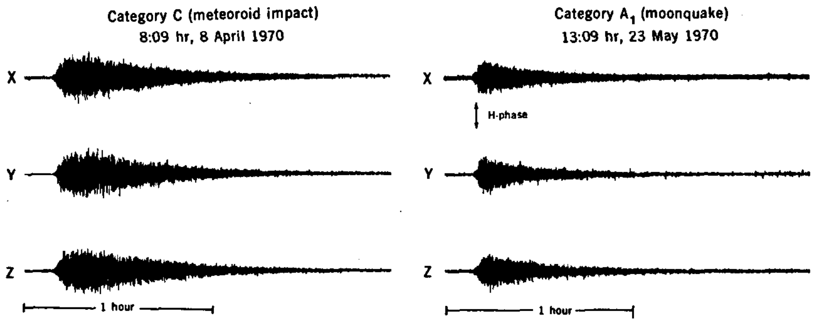


"wet"

"dry"

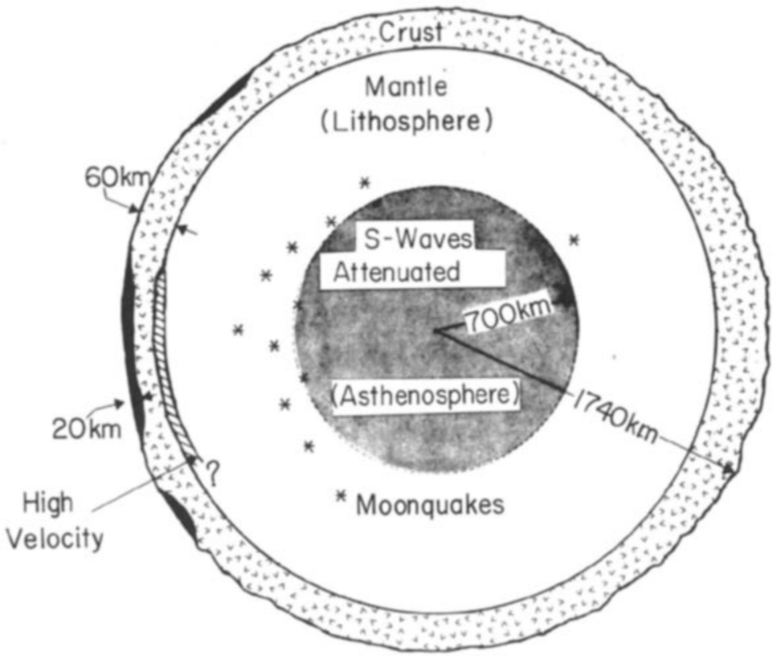
Aizawa et al. (2008)

Seismic Q of the Moon

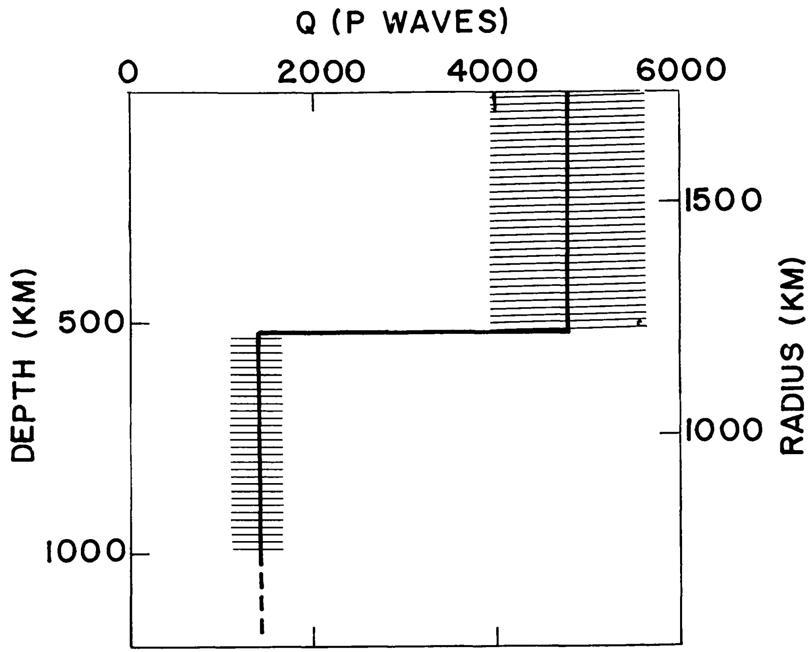


shallow Moon: very high Q

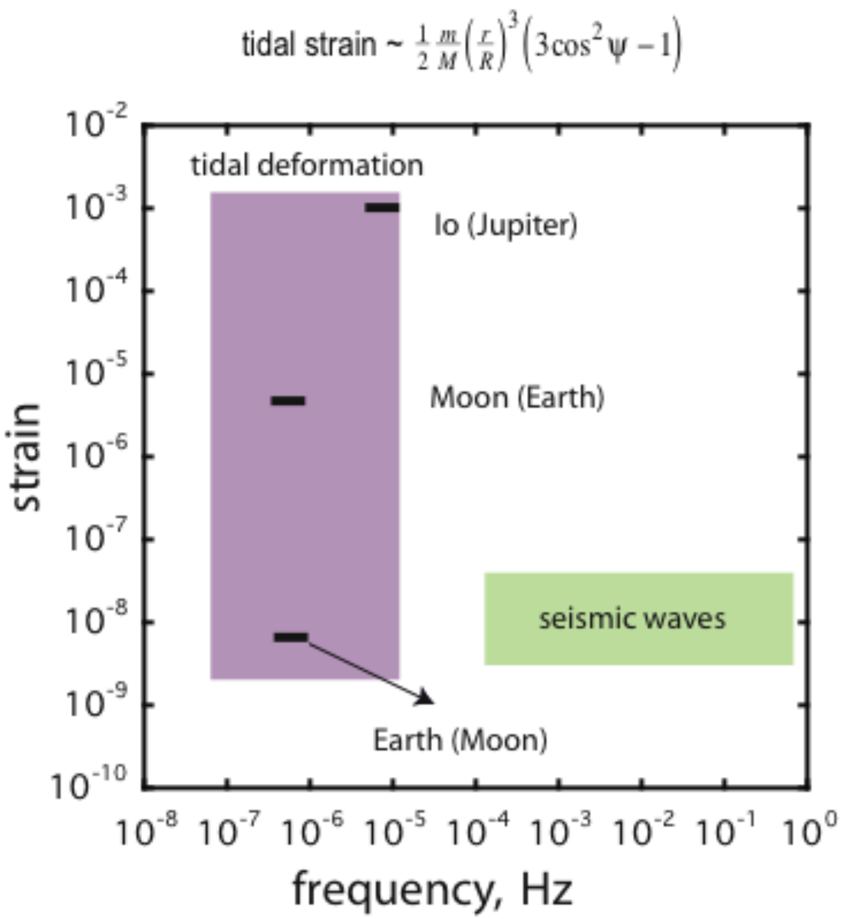
deep Moon: lower Q (but poorly constrained by seismological obs.)

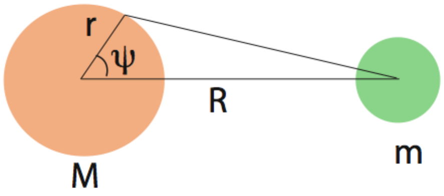


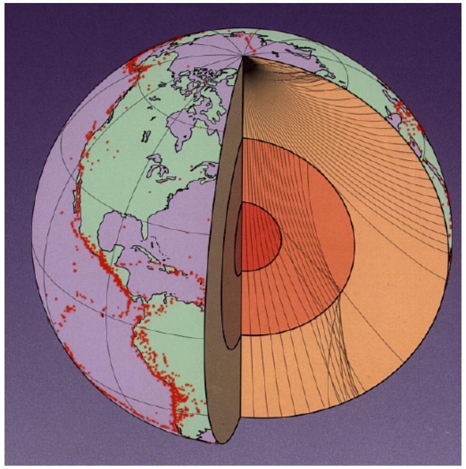
Toksöz (1974)



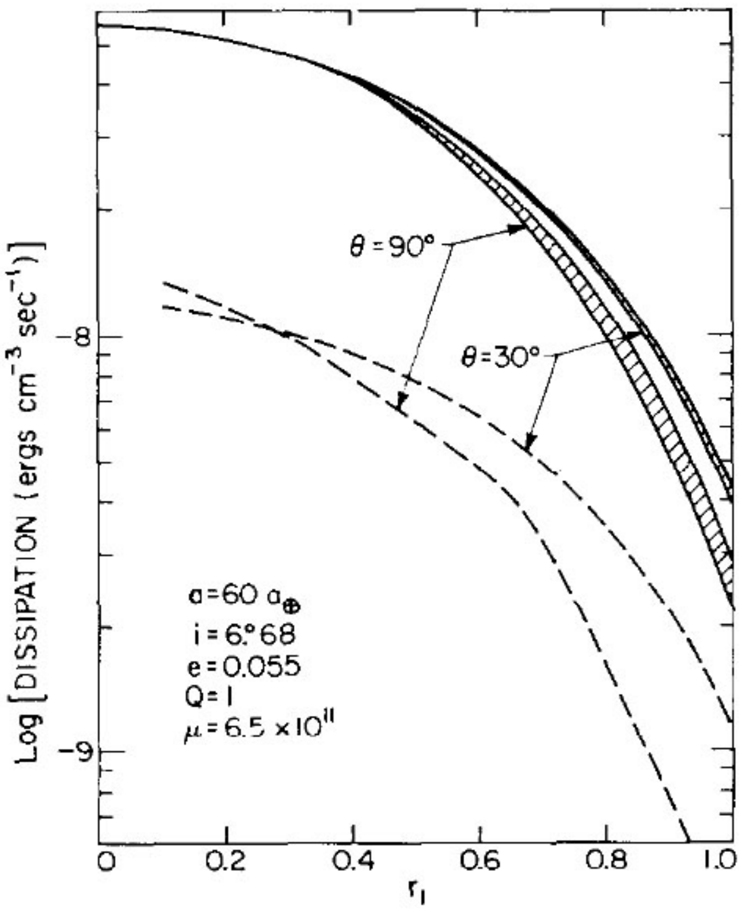
tidal deformation
(tele-)seismic wave propagation



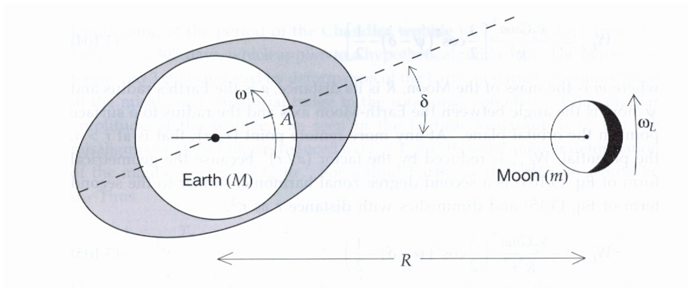




Tidal dissipation → Q of the deep mantle

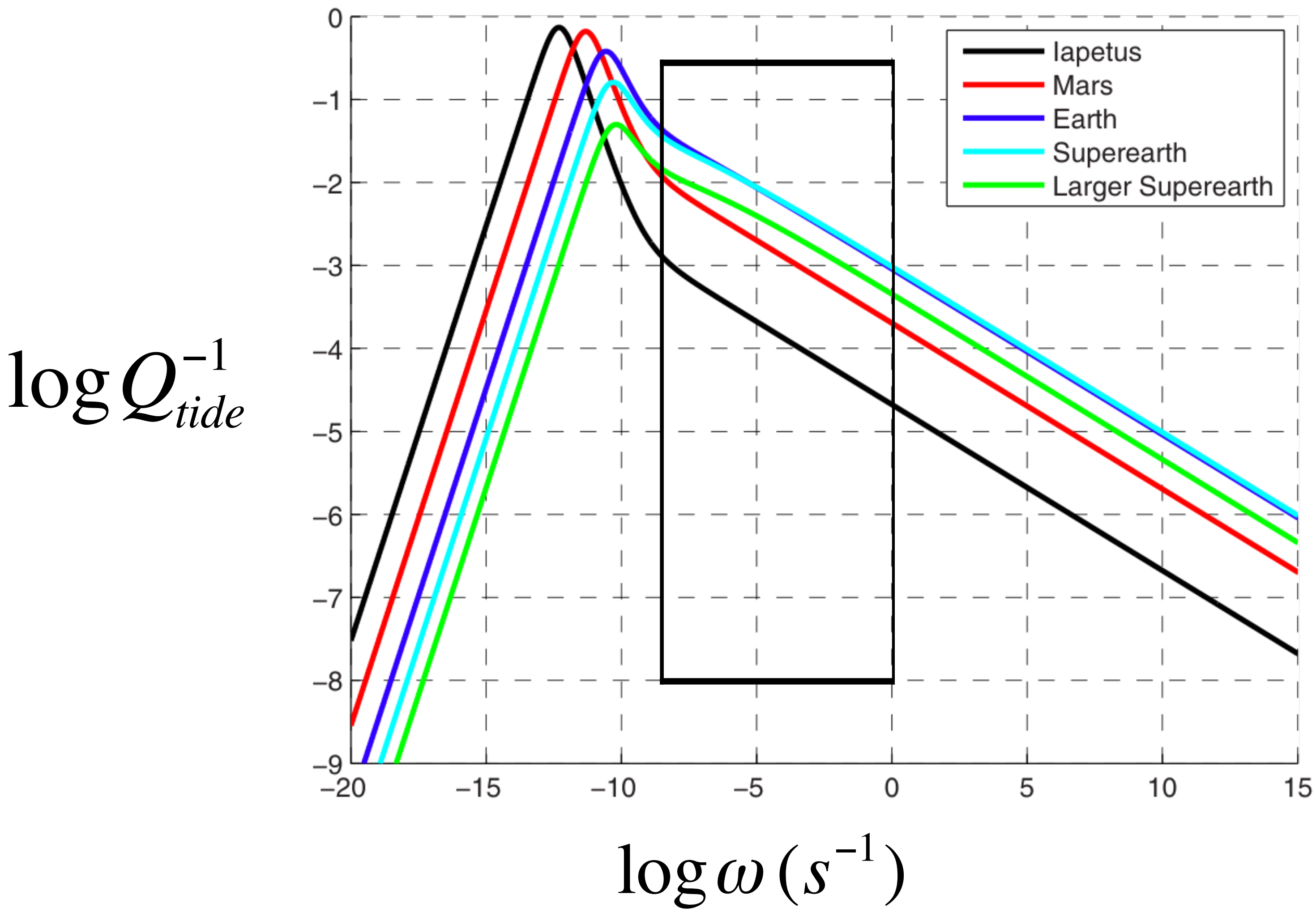


(Peale and Cassen, 1978)



Energy dissipation occurs in most part in the deep interior of a planet.

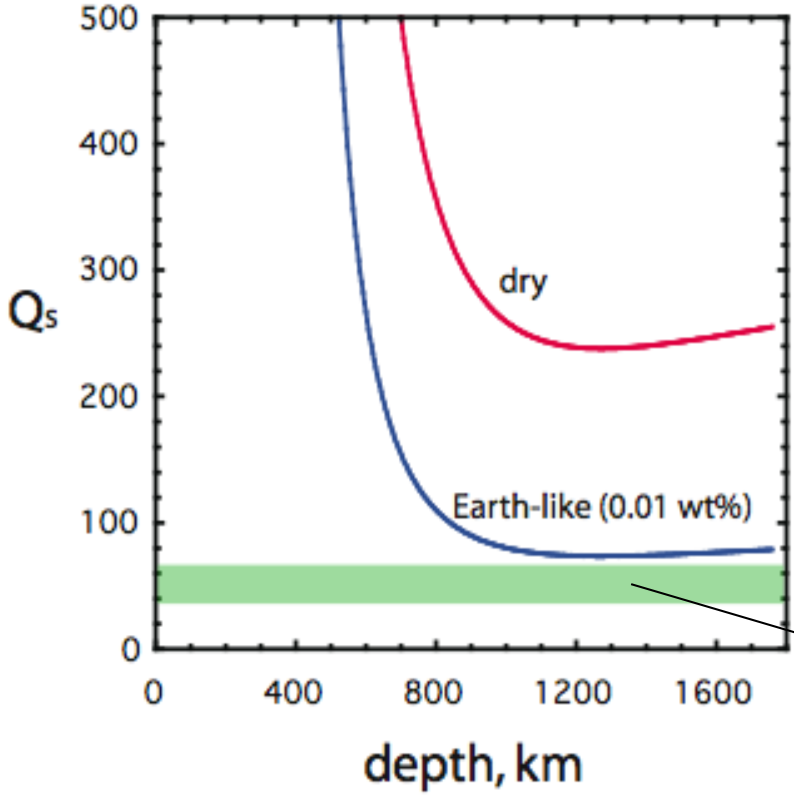
Frequency dependence of tidal Q



(after Efroimsky, 2012)

(viscosity = 10^{21} Pa s,
Elastic constant=10^{11} Pa)

Lunar Q model



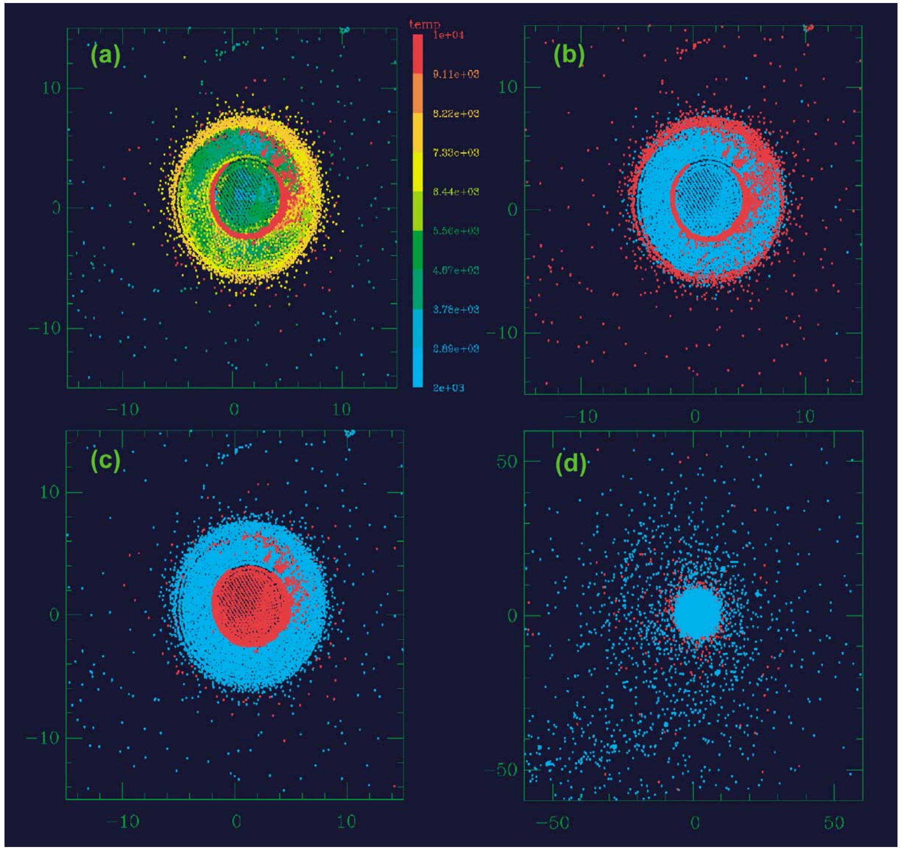
$$Q^{-1} / Q_0^{-1} = \left(C_W / C_{W0} \right)^{\alpha r}, \quad \alpha r = 0.3$$

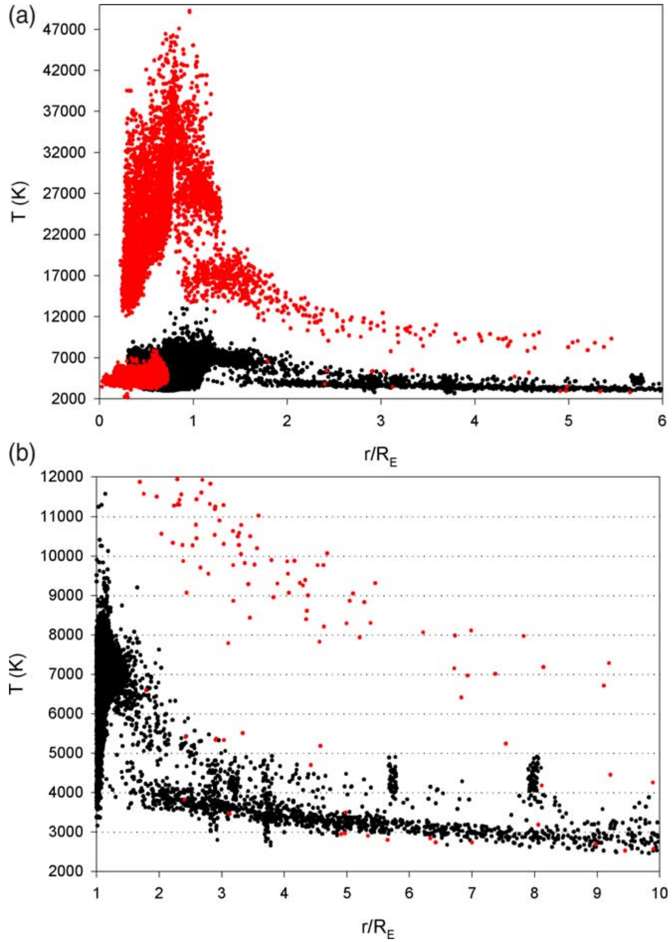
Water-rich (Earth-like) deep mantle ?

(Hauri et al., 2011)

Williams et al. (2001)

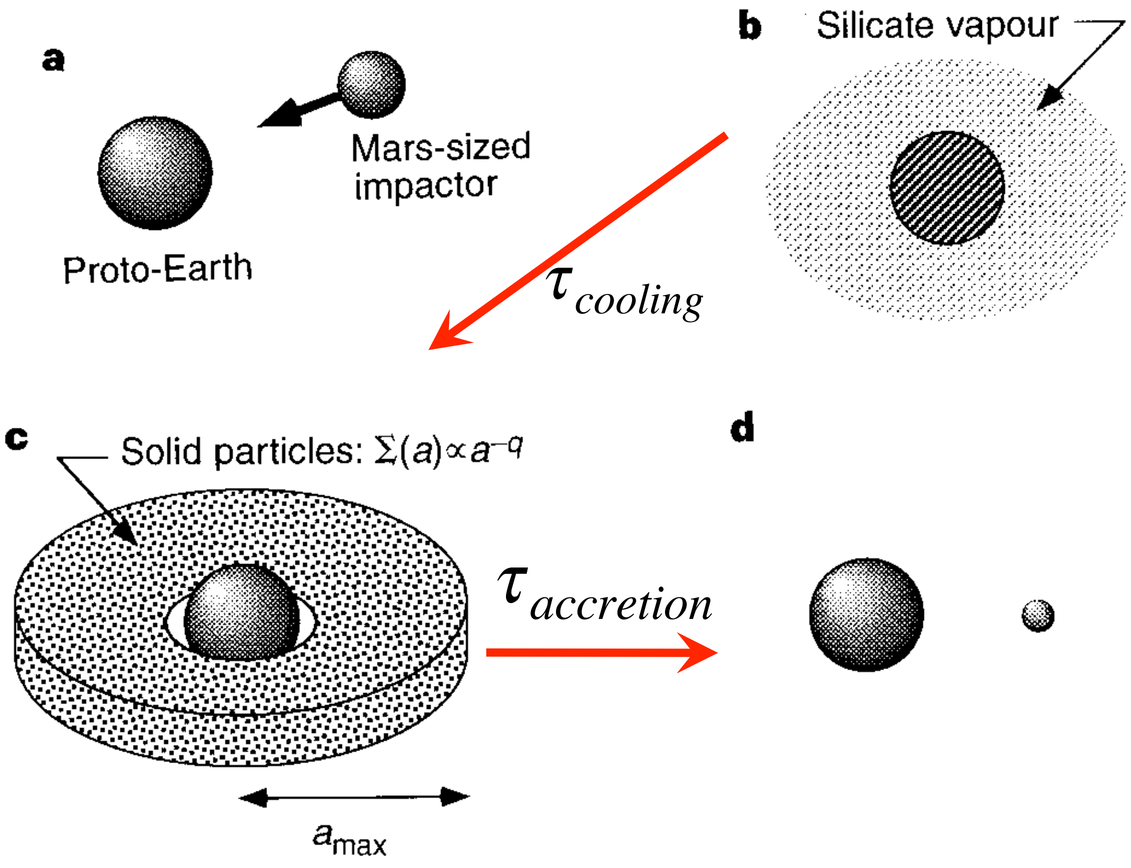
How could the Moon have acquired a substantial amount of water if it was formed by a giant impact?



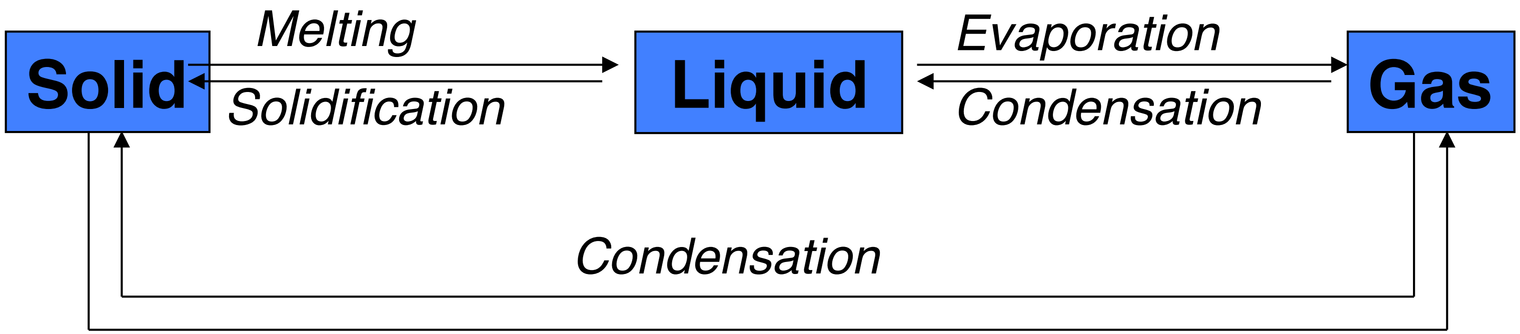


Canup (2004)

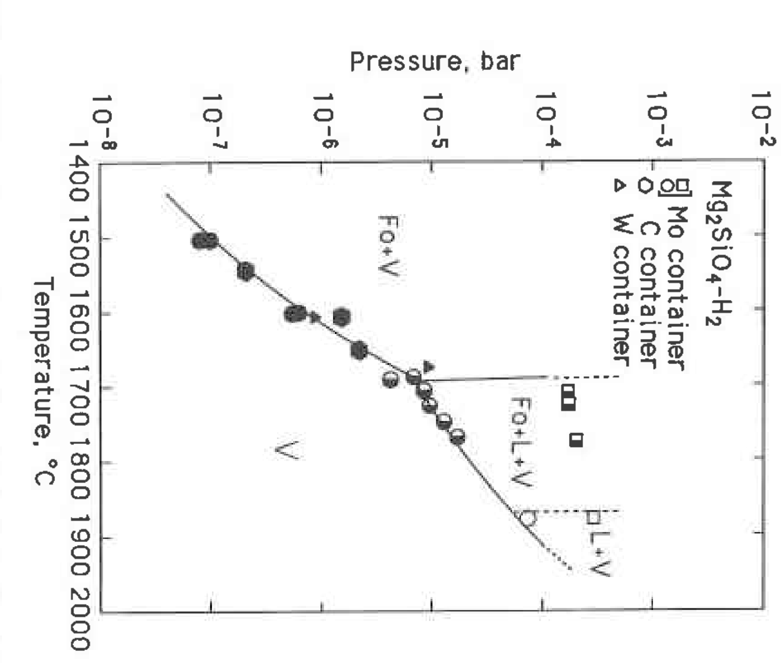
Volatiles during condensation, accretion



The sequence of condensation depends on P

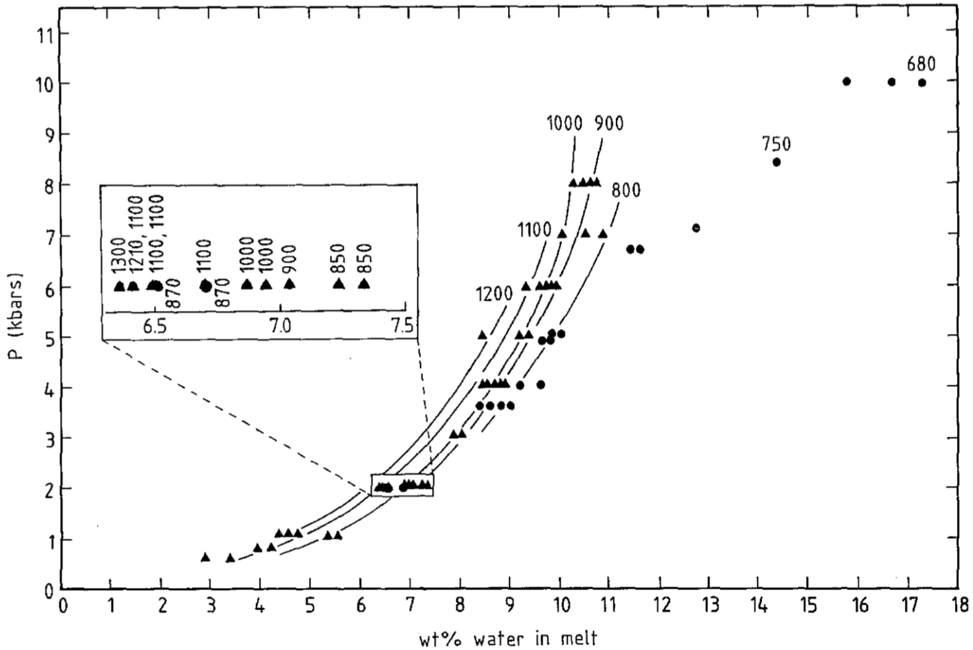


Sublimation: atoms or molecules escape into the gas phase from a solid.

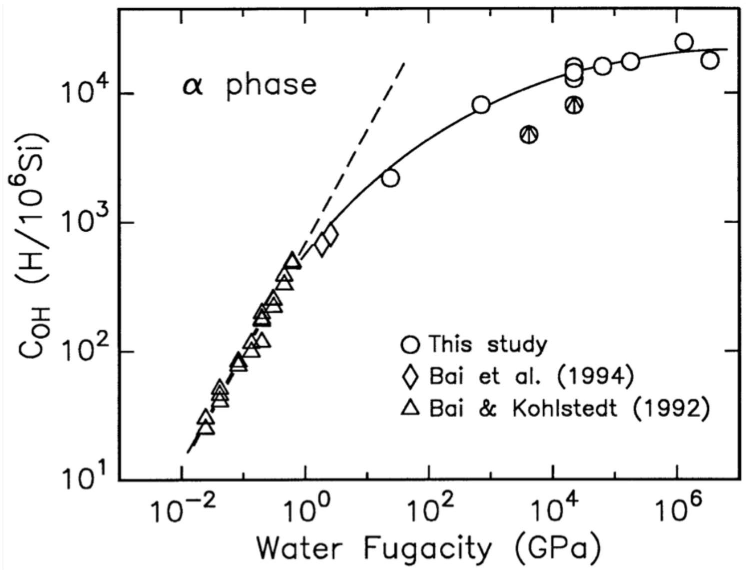


Water (hydrogen) solubility

(silicate melt)



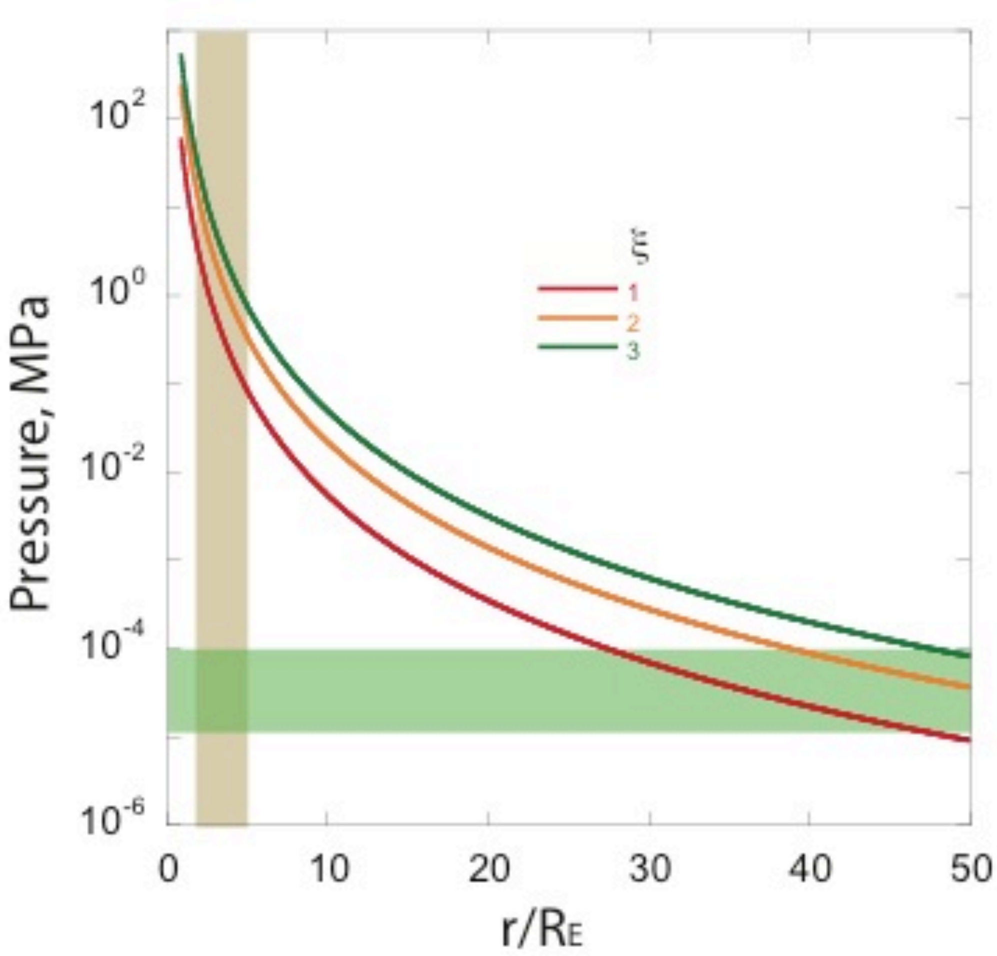
(olivine)

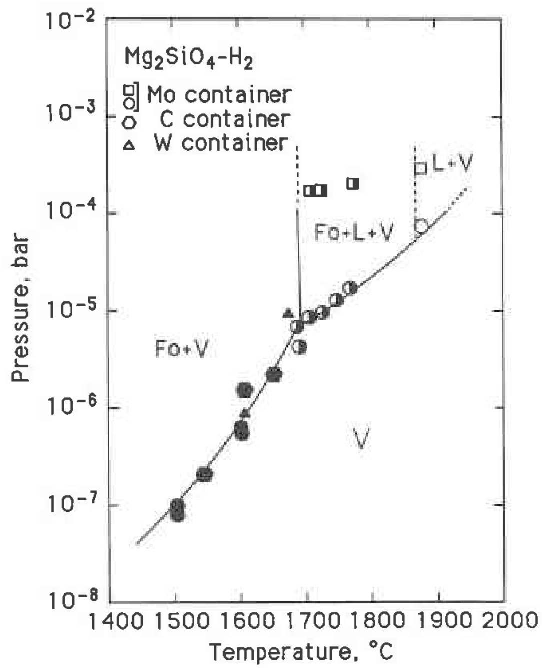


Water (hydrogen) solubility in melts is much larger than that in minerals.

10^3 (H/10^6 Si) =0.006 wt%

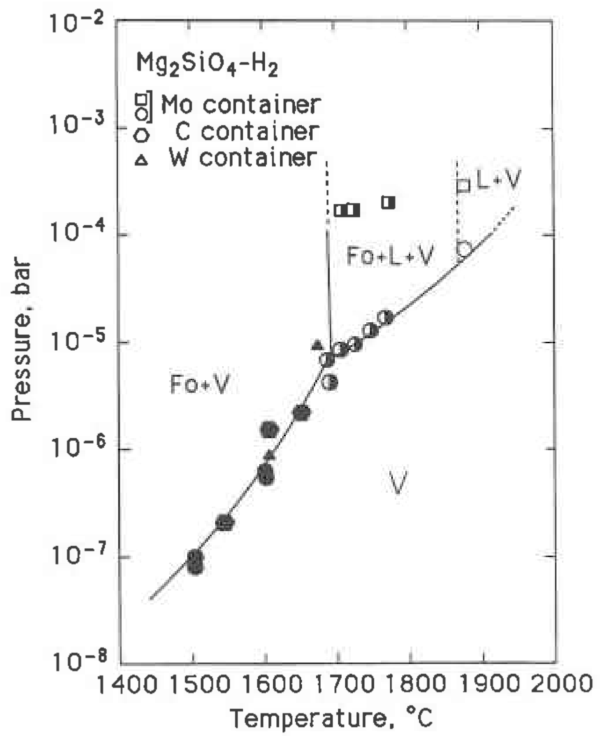
Initially condensed materials will be liquid phase if P is high
→ how high is the pressure of the Moon forming disk?

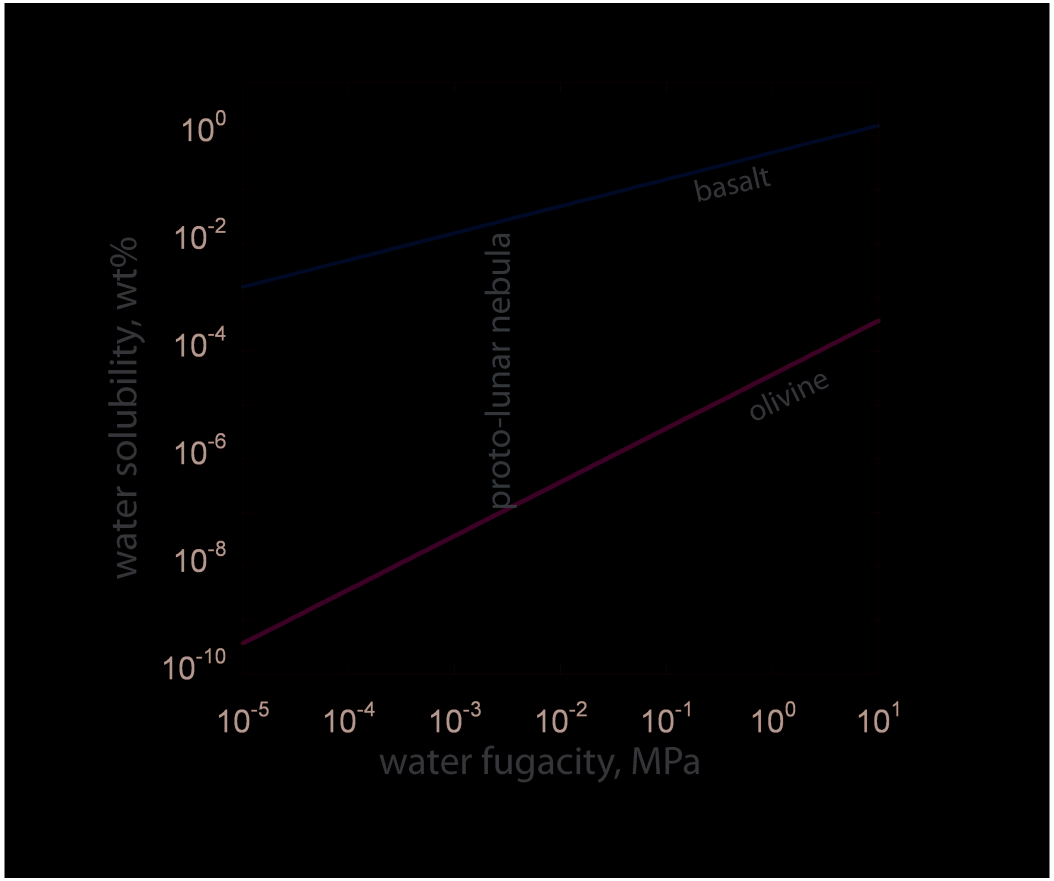




Mysen-Kushiro (1988)

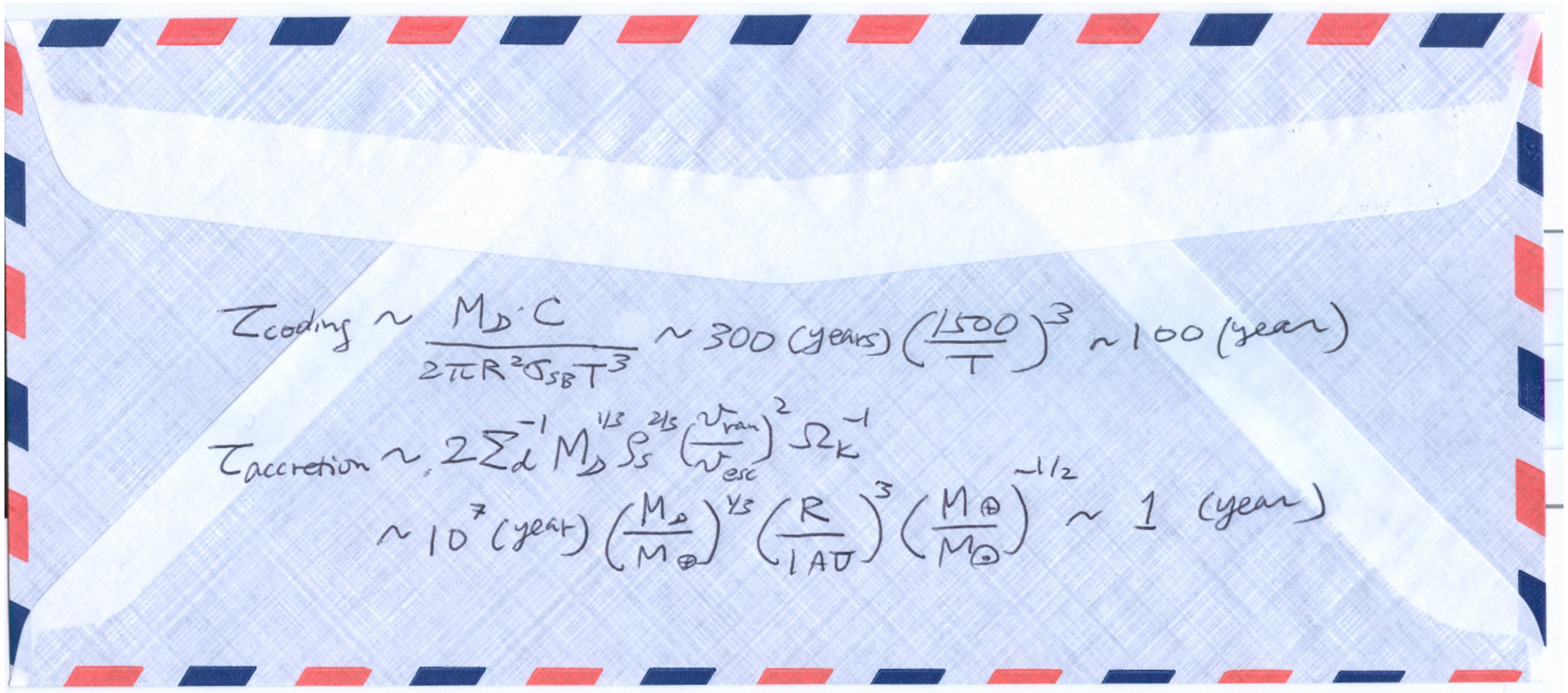
Liquids can dissolve a substantial amount of water

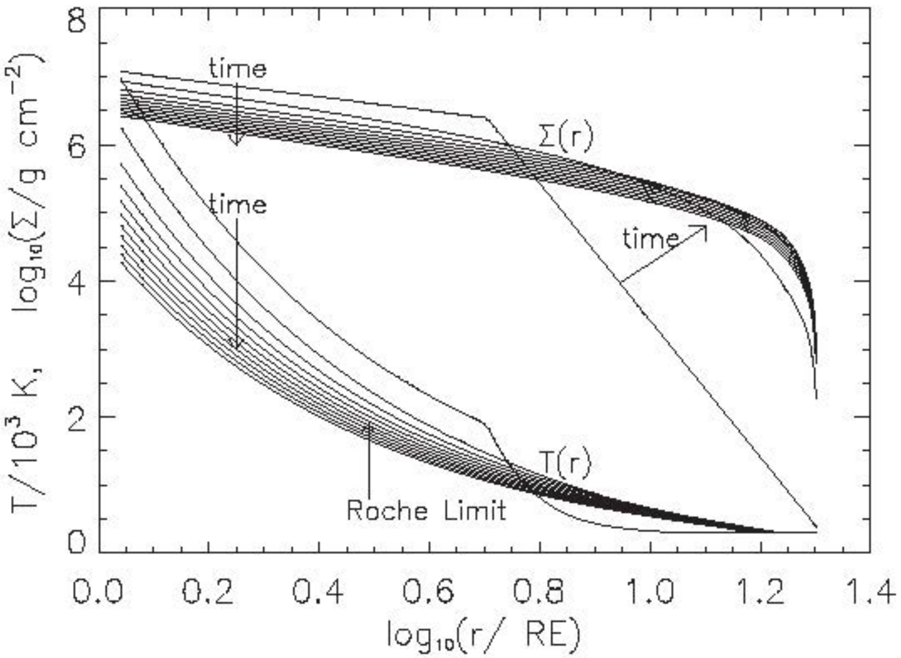




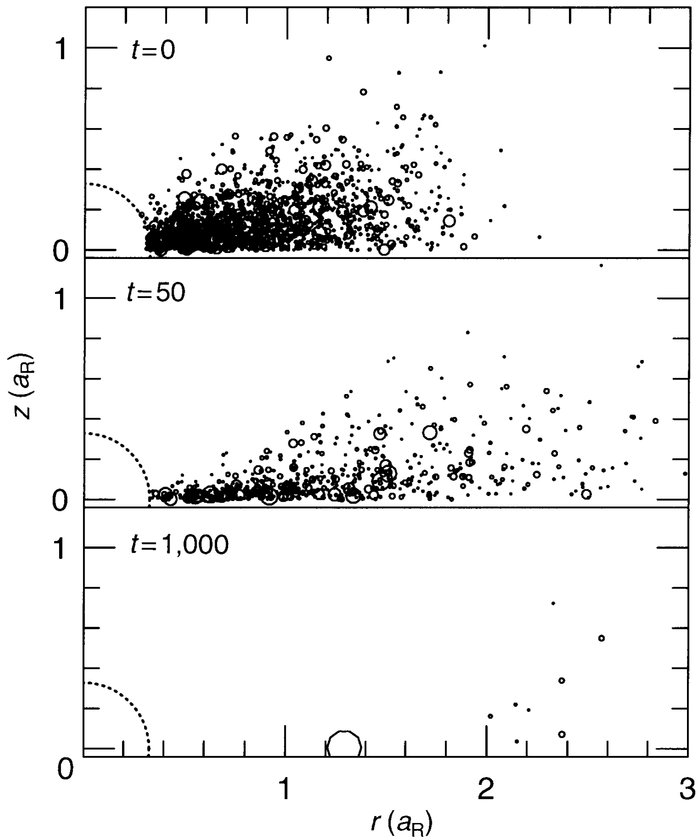
Cooling and accretion time scale

(in order to keep water, accretion must be quick)





Cooling time-scale~ 30 year
(Desch-Taylor, 2011)

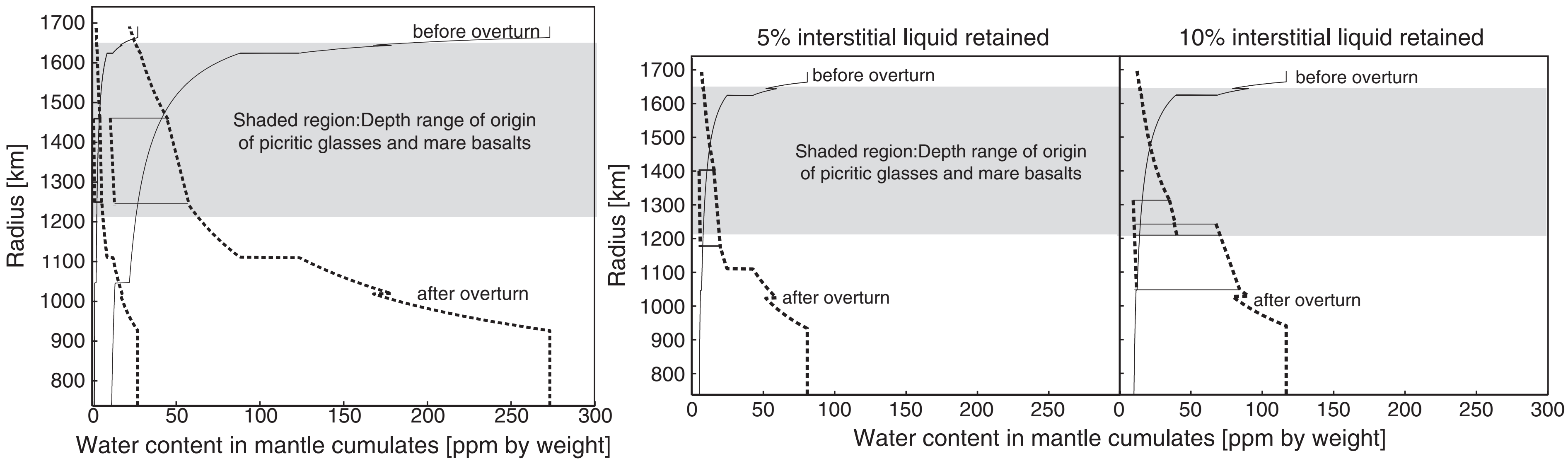


t=1000~1 year
(Ida et al. , 1997)

→ Cooling time scale is longer than accretion time scale
→ Accreted materials are mostly liquids
→ Initial materials for the Moon are “wet” (not so “dry”).

later stage

Cooling magma ocean leads to stratified water content.
→"dry" near surface, "wet" deep interior (consistent with geophysical observations)



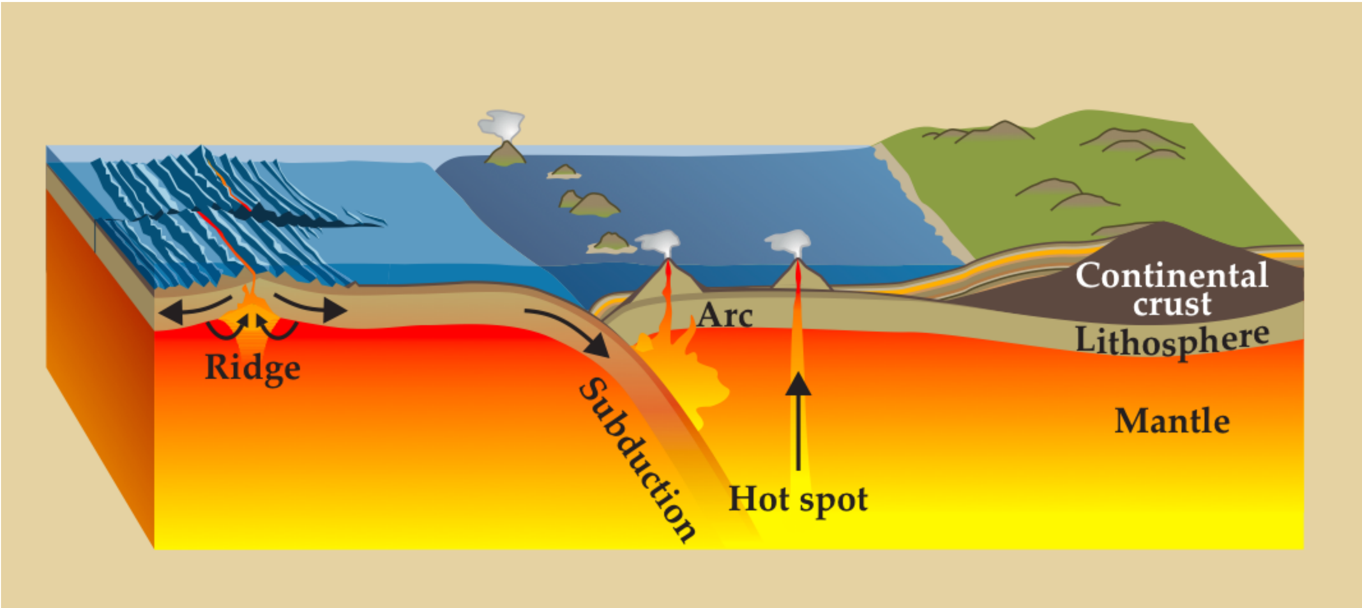
(Elkins-Tanton and Grove (2011))

conclusions

- The Moon's interior is not bone dry. ← electrical conductivity, tidal Q (~0.01 wt% water in the deep mantle (similar to the upper mantle of Earth))
- Condensation after a giant impact likely involves **liquid phases**. → if **cooling time scale > accretion time scale**, then a substantial amount of water can be acquired.
- After accretion, cooling magma ocean leads to stratification in water content → "wet" deep mantle, "dry" shallow mantle (explain geochemical and geophysical observations)

Evolution of ocean through geological history

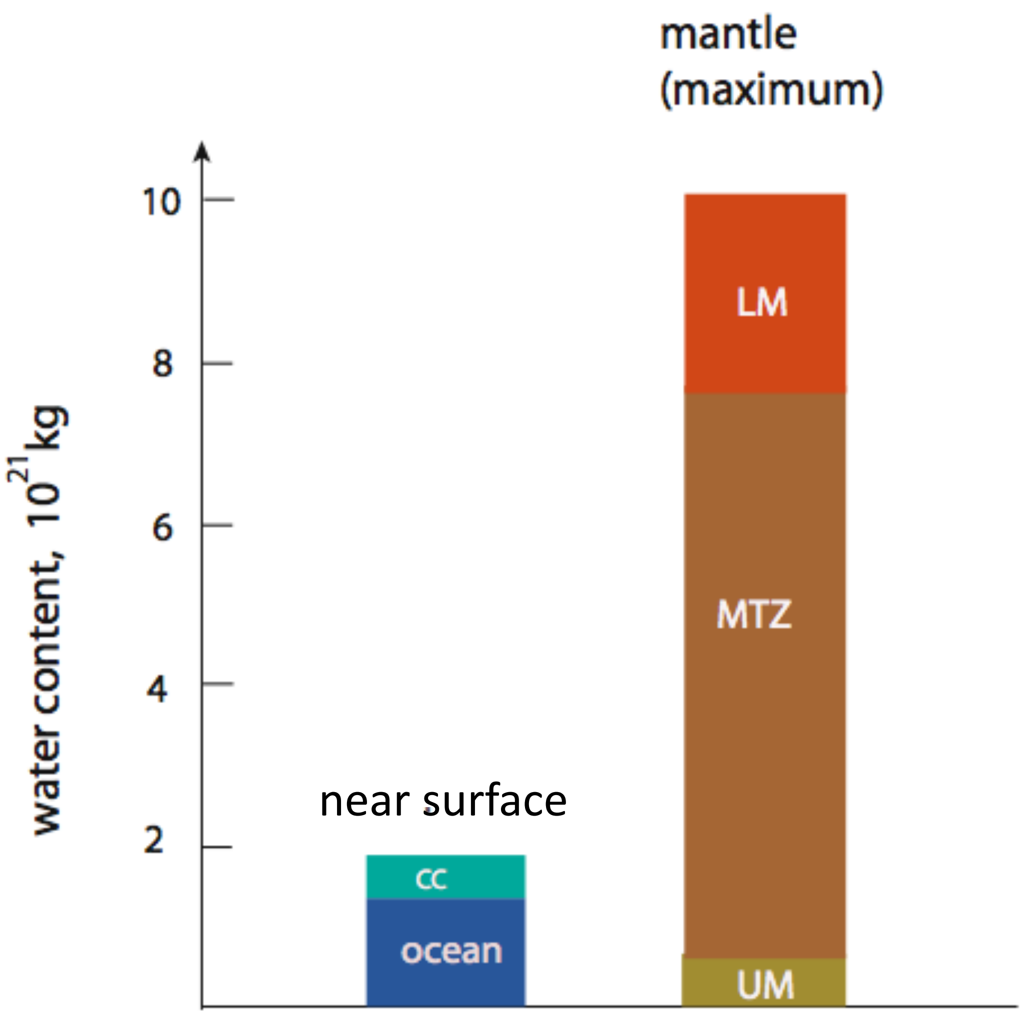
global volatile circulation ← **plate tectonics**

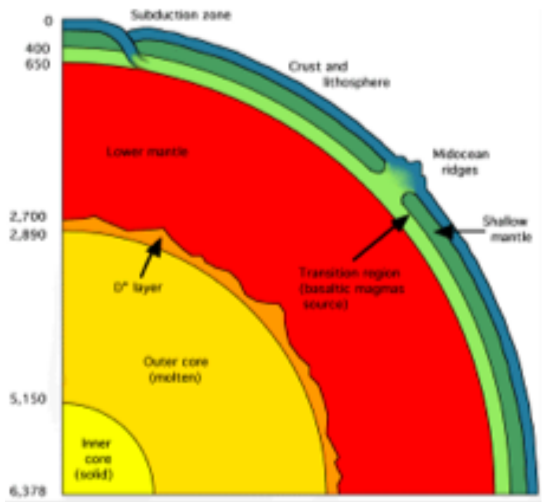


Earth's ocean is formed mostly from water inside of Earth.
Has ocean been there for billions of years? If so how is the ocean mass stabilized?

→ **How is water distributed in the current Earth's interior?**

→ What control the ocean mass evolution?





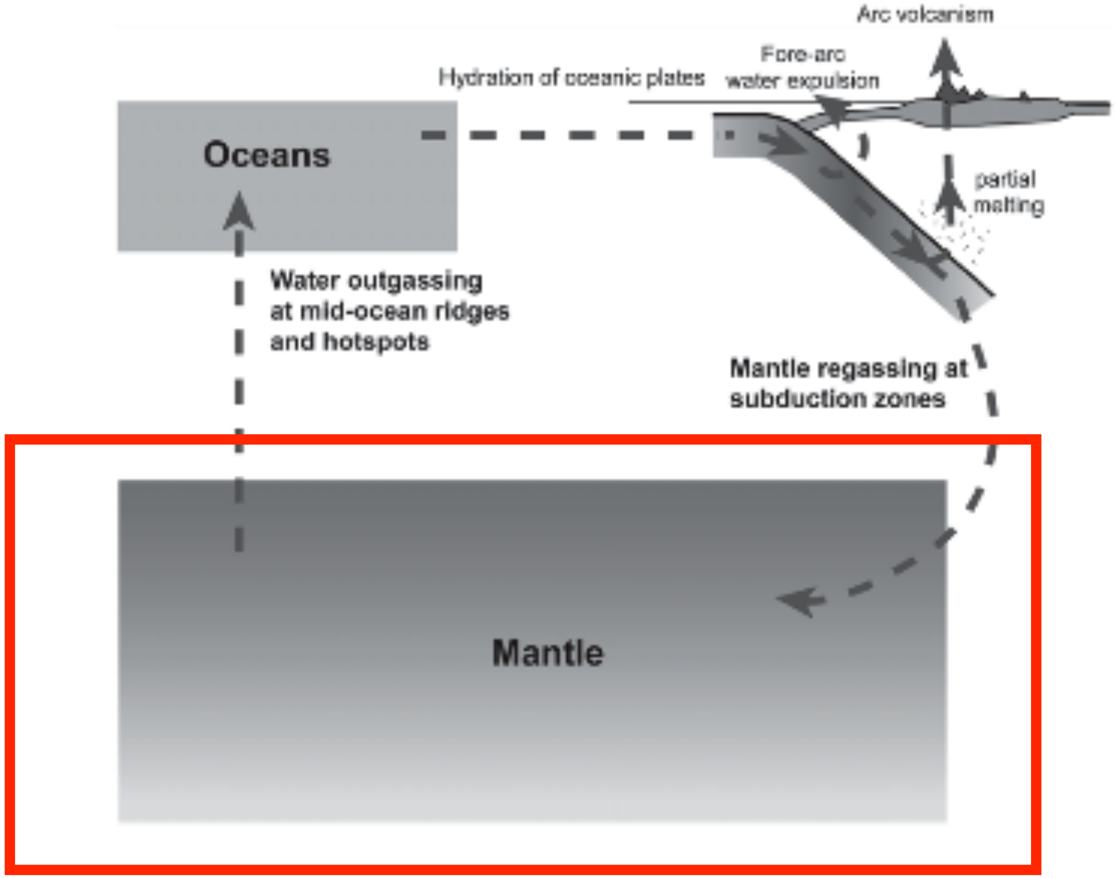
(+ water in **the core**)

Earth's interior is **potentially** a big water reservoir.
But how much is there really?

Ocean has been formed by global water circulation.

→ ocean mass is controlled by deep mantle processes

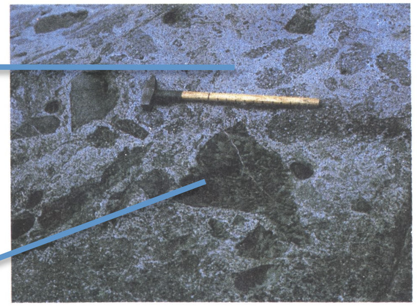
(if mantle is homogeneous, then ocean mass is sensitive to regassing rate)



McGovern-Schubert (1989)
Franck-Bounama (2001)
Rüpke et al. (2006)
Korenaga (2008)

Water distribution in the mantle from geological observations

- **From basalts** (Ito et al., 1983; Dixon et al., 2002)
  - Indirect (needs a model of melting)
  - "global" (MORB, OIB)



a

- **From mantle rocks** (Bell and Rossman, 1992)
  - direct
  - limited to shallow upper mantle
  - influence of loss/gain needs to be evaluated

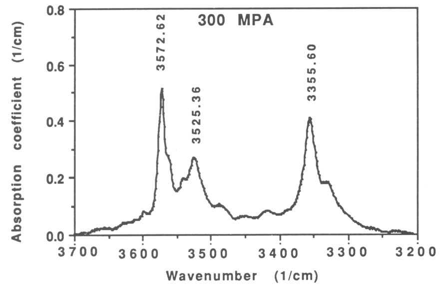


Table 1. Estimates[1] used in Figure 1.

	oceanic ridge magmatism	hotspot magmatism	arc magmatism	subduction of altered oceanic crust	subduction of amphibole in altered oceanic crust	subduction of sediments[2]
rock[3] ($\times 10^{15}$ g/yr)	+56	+4.4	+0.5 to 10	-56(60.4)[4]	-0.7 to 3.7	-1.8 to 3.5
H_2O (wt%)	0.2	0.305	2	1 to 2	2	2.5 to 20
Cl (ppm)	48	290[5]	900	25 to 75	150	430 to 2500
density (g/cm^3)	2.9	2.9	2.8	2.9	3.1	1.2 to 2.3
volume ($\times 10^{15}$ cm^3/yr)	20	1.5	1.2 to 3.6	0.25 to 1.2	1.5	
thickness (km)	6.5	—	--	5.5	--	0.5

Ito et al. (1983)

Table 1 **Dehydration efficiency**

Rock	Ce (p.p.m.)‡	H_2O/Ce	H_2O (wt%)	Dehydration (%)
Crustal components: Pre-subduction				
Atlantic MORB*	12	250	0.3	
Pacific MORB*	14	150	0.2	
Mature oceanic crust*	~6	2,500–5,000	2–3	
Global subducted sediment†	57	1,280	7.3	
Crustal components: Post-subduction				
Mature oceanic crust	~6	~100	0.06§	97
Global subducted sediment	57	<100	<0.57	>92
Mantle components				
DMM*	0.5	200	0.010	
Atlantic FOZO‖	3	250	0.075	
Pacific FOZO¶	3.8	200	0.075	
EM#	4	<100	<0.04	

Dixon et al. (2002)

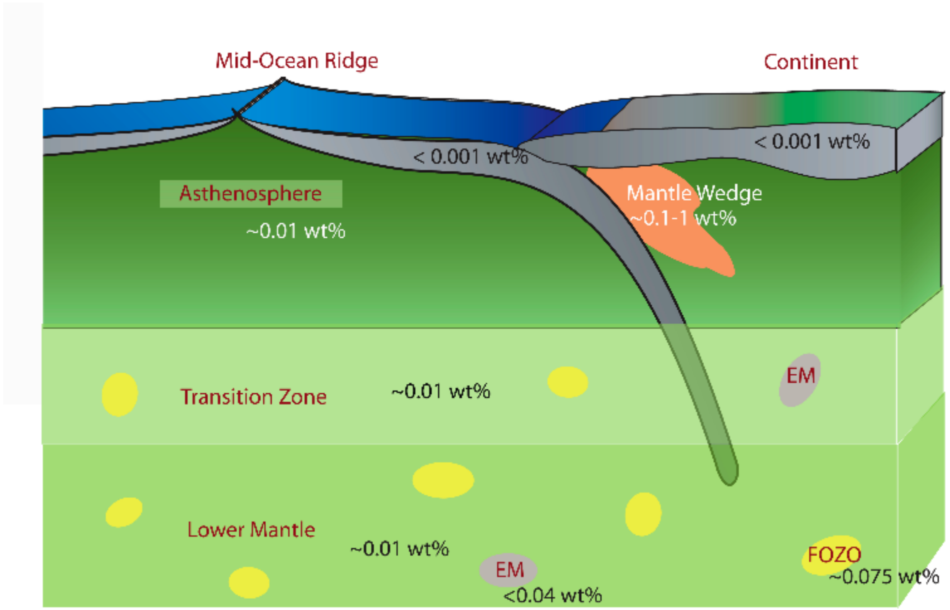
MORB source region (asthenosphere): well constrained (~0.01 wt%)

OIB source regions: water-rich (FOZO) (~0.1 wt%)

How are they distributed?

- localized?
- global (layered)?

A conventional model of water distribution in the mantle



Franck-Bounama (2001)
Dixon et al. (2002)
Rüpke et al. (2006)

$$\frac{\partial H_2O_{mantle}}{\partial t} = -\xi_{H2O} \cdot R(t) \cdot H_2O_{mantle}(t) + S(t)$$

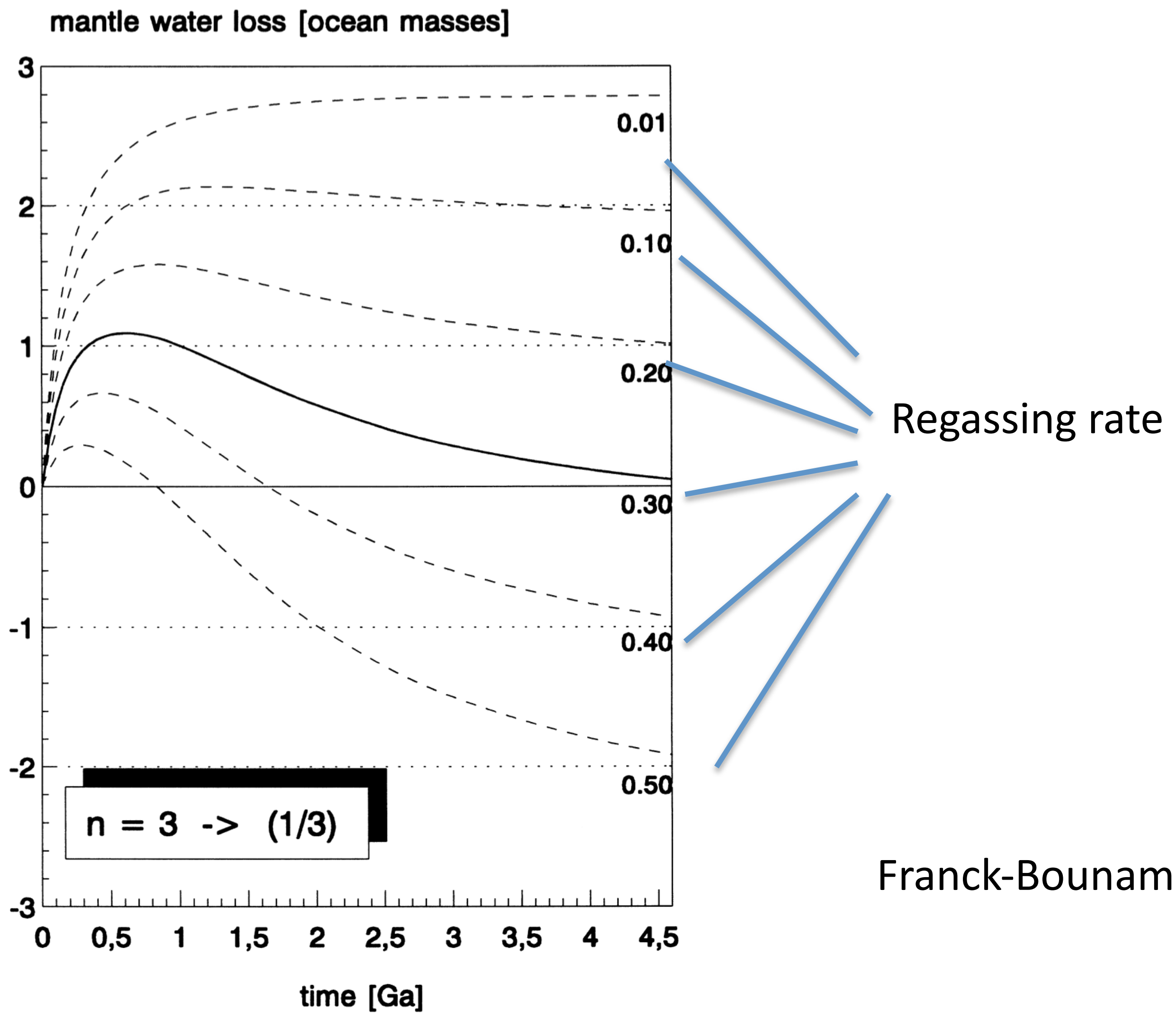
$$\frac{\partial H_2O_{ocean}}{\partial t} = \xi_{H2O} \cdot R(t) \cdot H_2O_{mantle}(t) - S(t)$$

$R(t)$: mantle processing (degassing) rate

$S(t)$: water recycling (regassing) rate

Geochemical approach (MORB, OIB) + simple geodynamic modeling

→ **“plum pudding” model**



Franck-Bounama (2001)

The ocean mass changes sensitively to the regassing rate in a single component mantle model.

Geochemical approach + simple model → "plum pudding" model
→ inconsistent with the definition of **FOZO**
(a common component of all OIB)

→ ocean mass is sensitive to mantle water (unstable)

What is wrong??

1. Spatial distribution of water is poorly constrained by the geochemical approach.
→ "plum-pudding" model may be wrong.

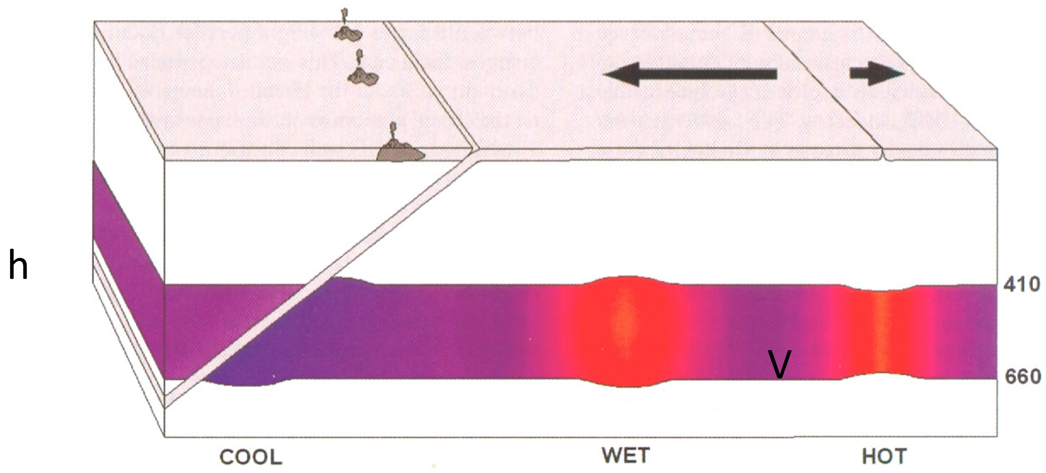
2. Whole mantle is treated as a single unit.
→ there may be some buffering processes that requires additional parameter in the modeling.

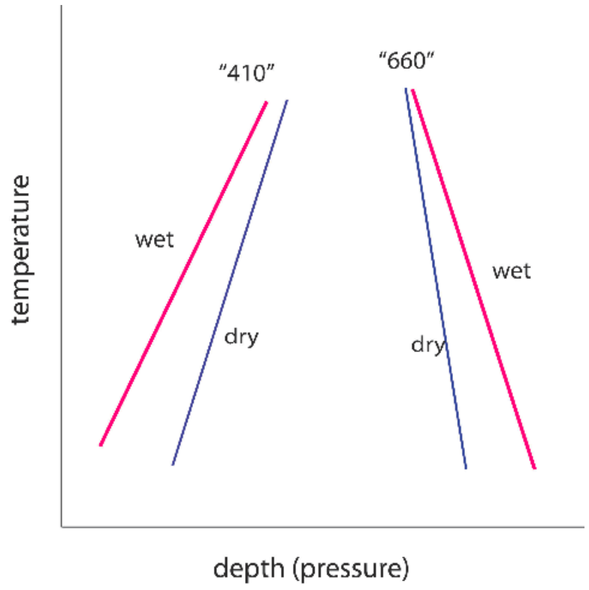
Any observations to suggest internal processes controlling water circulation? → geophysical approach

Water distribution in the mantle from geophysical observations

- **From electrical conductivity**
  - direct (sensitive to water content but insensitive to major element chemistry)
  - lab study is a little complicated, but **a good data set is now available.**
  - large uncertainties in geophysical observations
- **From seismological observations**
  - Indirect (modestly sensitive to water content but sensitive to major element chemistry)
  - lab study is incomplete (Q-effect).
  - high-resolution observations

Water may affect seismological observations





- T-effect and water-effect on seismic wave velocities
- T-effect and water-effect on the phase boundary

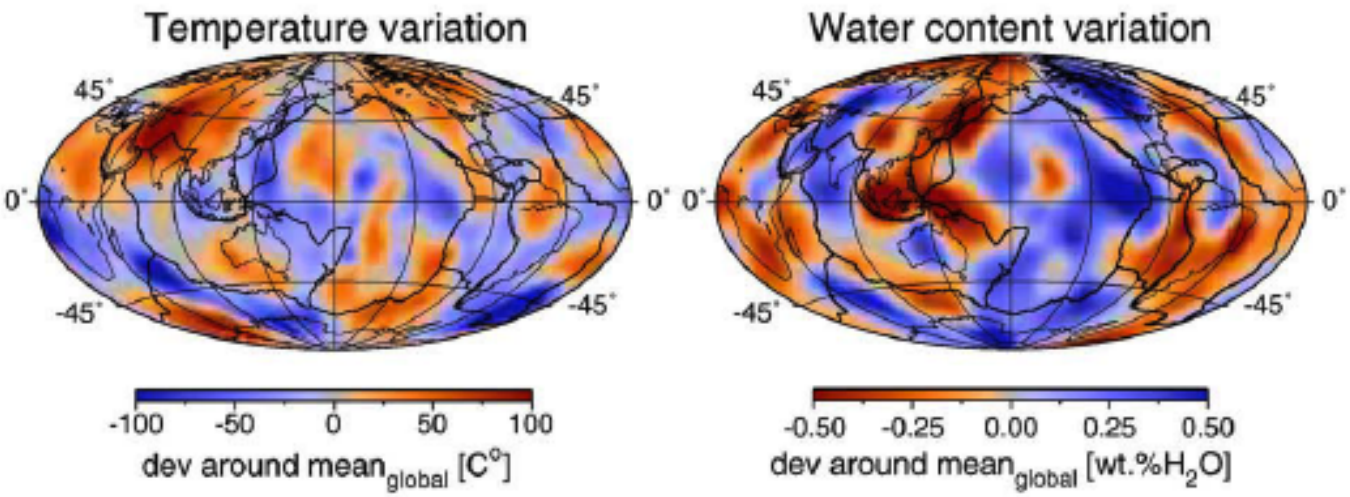
$$\begin{pmatrix} \delta \log V \\ \delta h \end{pmatrix} = \begin{pmatrix} \frac{\partial \log V}{\partial T} & \frac{\partial \log V}{\partial C_W} \\ \frac{\partial h}{\partial T} & \frac{\partial h}{\partial C_W} \end{pmatrix} \begin{pmatrix} \delta T \\ \delta C_W \end{pmatrix}$$

$$\rightarrow \begin{pmatrix} \delta T \\ \delta C_W \end{pmatrix} = \begin{pmatrix} \frac{\partial \log V}{\partial T} & \frac{\partial \log V}{\partial C_W} \\ \frac{\partial h}{\partial T} & \frac{\partial h}{\partial C_W} \end{pmatrix}^{-1} \begin{pmatrix} \delta \log V \\ \delta h \end{pmatrix}$$

Water-temperature distribution from $V_{P,S}$ and MTZ thickness

$$\delta d = \frac{\partial d}{\partial T}\delta T + \frac{\partial d}{\partial H_2O}\delta H_2O,$$

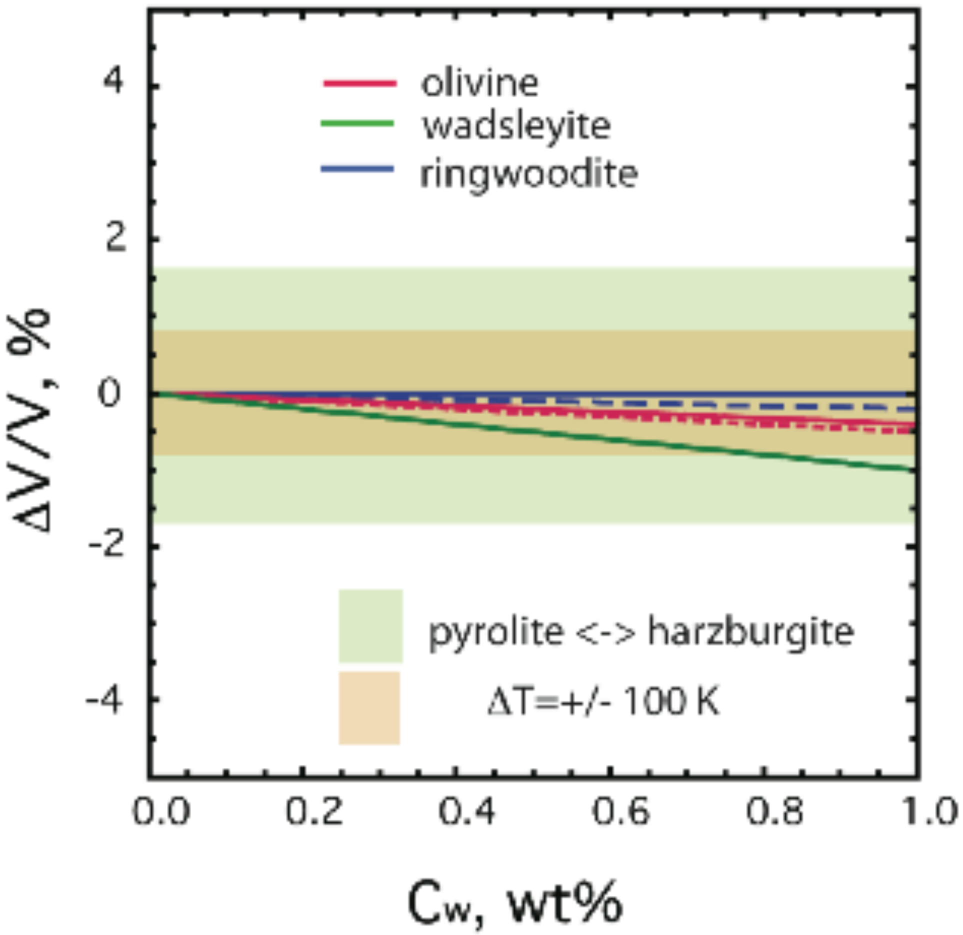
$$\delta \ln V_s = \frac{\partial \ln V_s}{\partial T}\delta T + \frac{\partial \ln V_s}{\partial H_2O}\delta H_2O,$$



Meier et al. (2009)

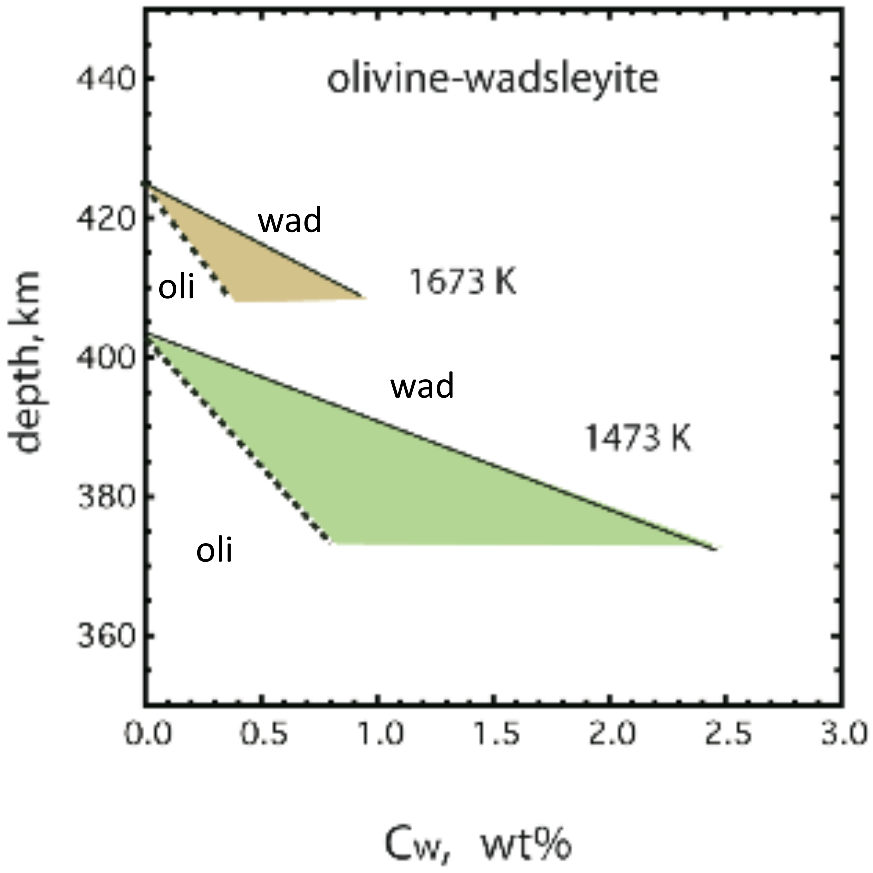
puzzling results ← due to the insensitivity of seismological properties to water content?

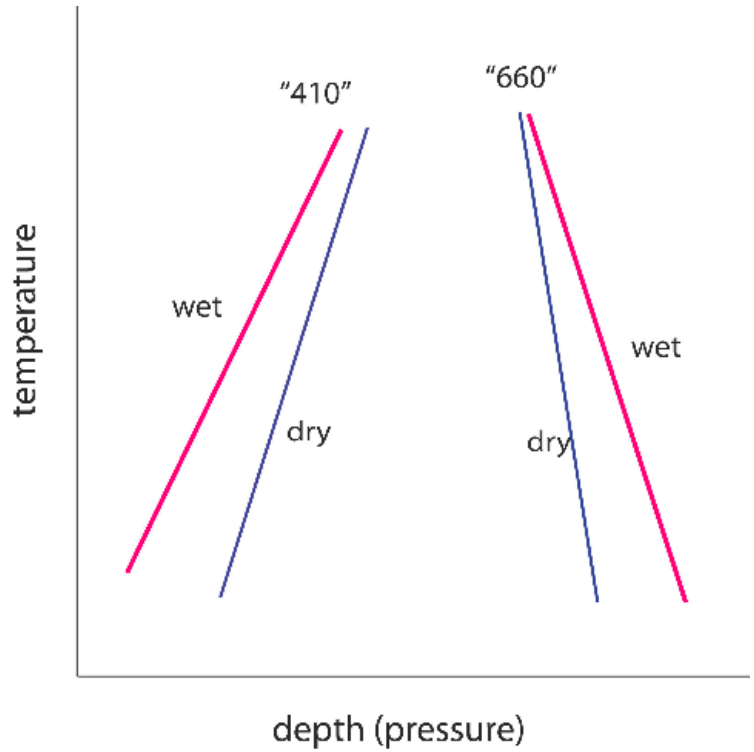
seismic wave velocity depends weakly on water content but strongly on the major element chemistry and T



Karato (2011)

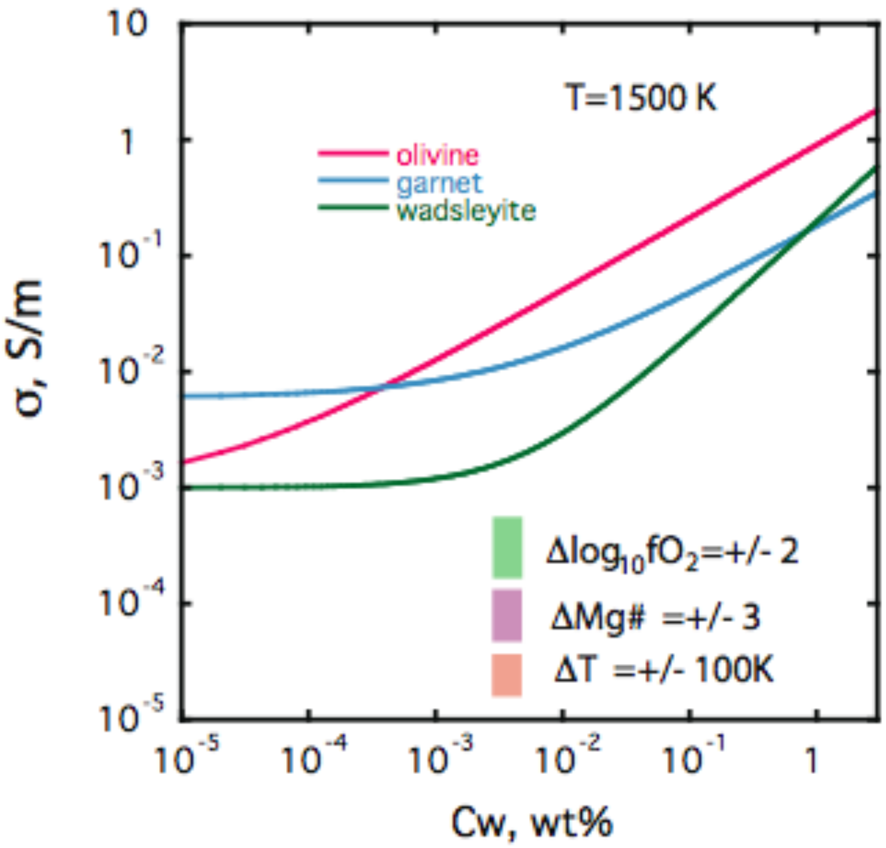
Influence of water on seismic discontinuities





Karato (2011)

Electrical conductivity depends strongly on water content
(relatively weakly depends on T and other factors)



Karato (2011)

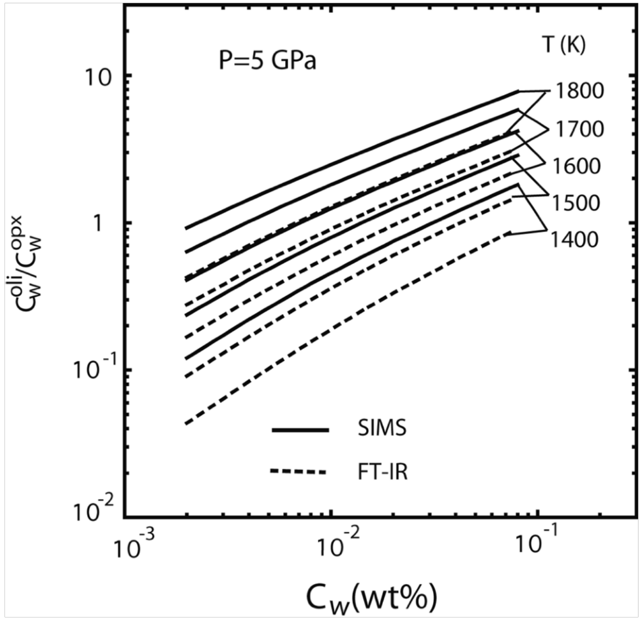
Sensitivity of some geophysical observables to water content

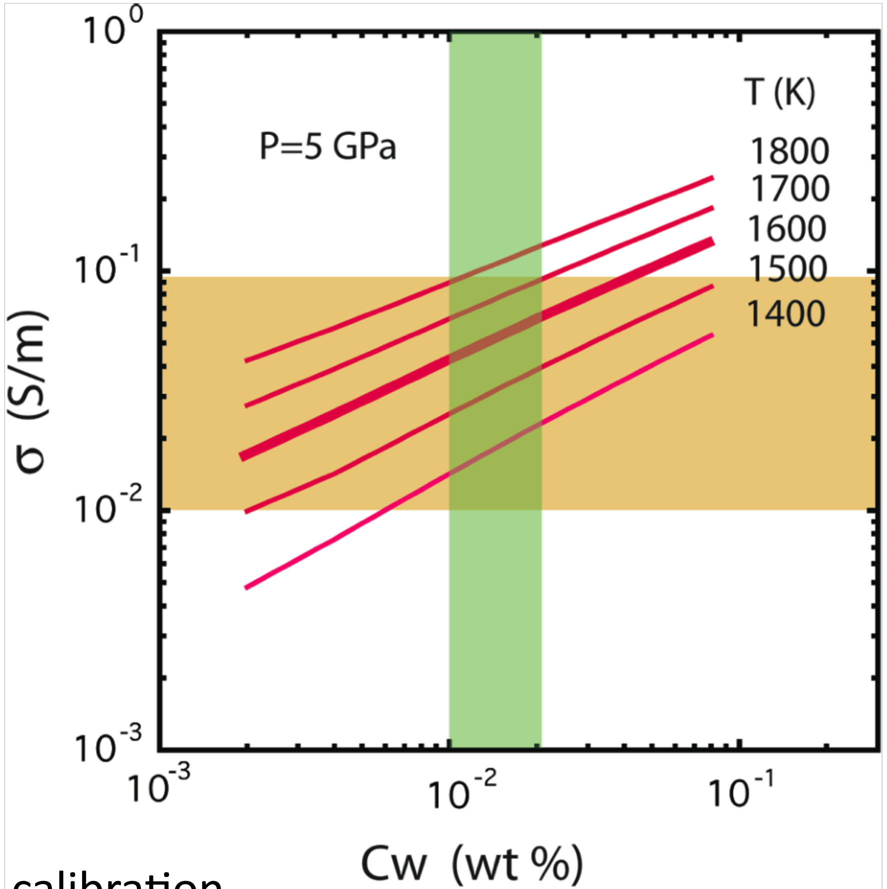
	sensitivity to:				*resolution of geophysical observations*
	T	*C (major)*	*C (water)*	*d*	
Seismic velocity	○	○	△	X	●
Seismic discontinuity	○	○	△	X	●
Seismic Q	○	X	● ?	△	△
Seismic anisotropy	△	X	●*	△	○*
Electrical conductivity	△	△	●	X	●

*: mostly for the upper mantle

Properties involving thermally activated processes are sensitive to water content.
Lab studies are more complete for electrical conductivity than for Q and LPO.

Testing the model for the upper mantle





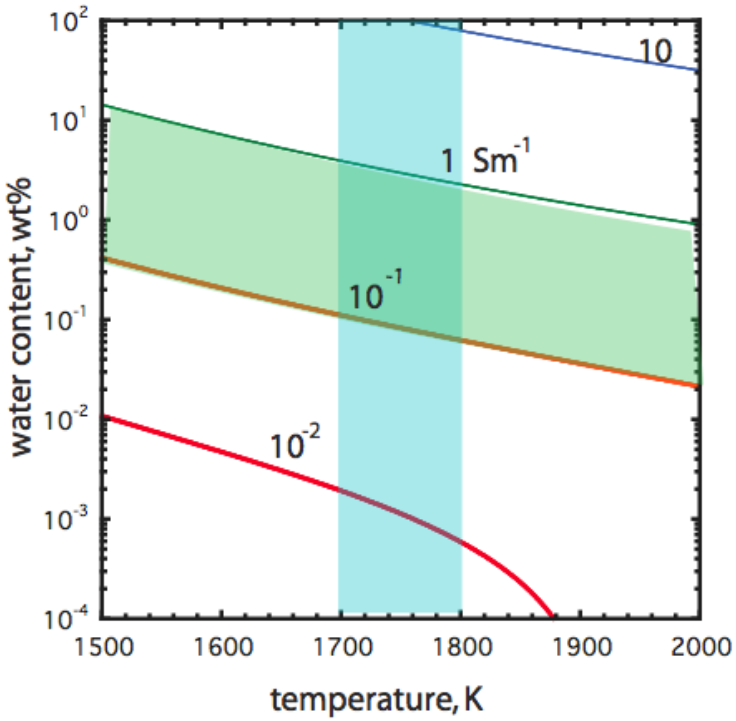
pyrolite (olivine+opx+pyrope), SIMS water calibration

[Dai and Karato (2009)]

$$\sigma = \sigma_{wad}\left(1 + \frac{1-\phi}{\frac{1}{\sigma_{gar}/\sigma_{wad}-1}+\frac{\phi}{3}}\right) = \alpha \cdot \sigma_{wad}$$

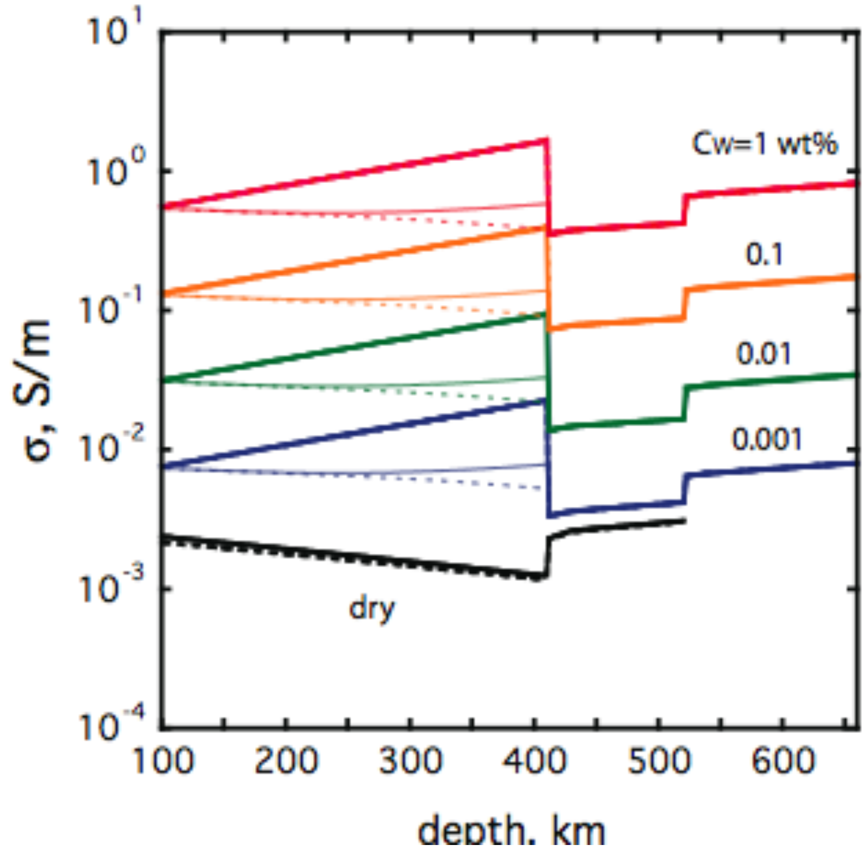
$$\alpha = 0.65$$

$$\sigma_{wad} = A \cdot C_W^r \cdot \exp\left(-\frac{H_{CW}^*}{RT}\right) + B \cdot \exp\left(-\frac{H_{CD}^*}{RT}\right)$$

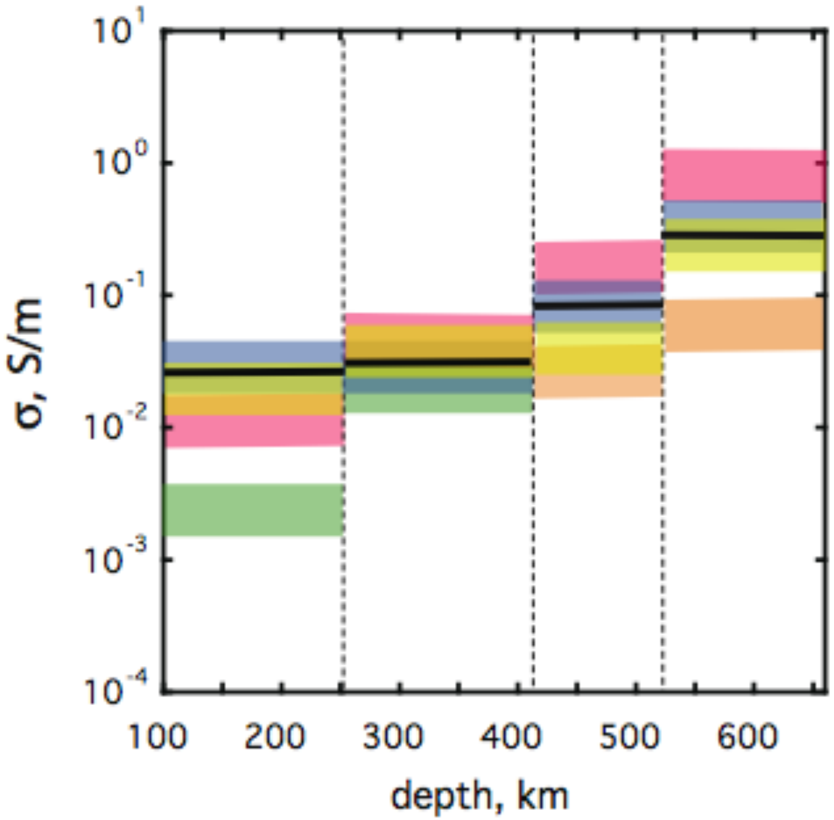


Electrical conductivity and water in the mantle

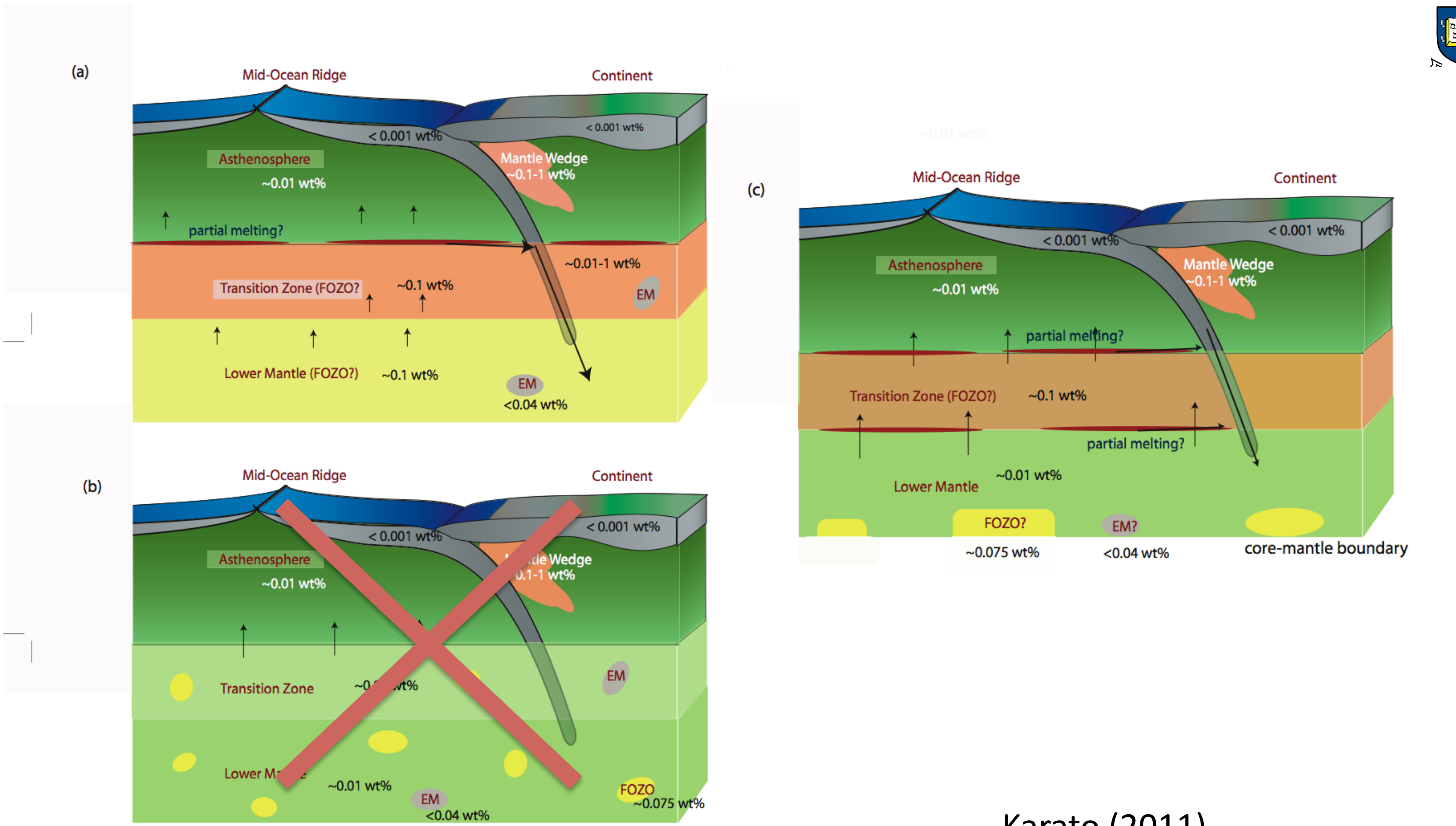
Mineral physics model



Geophysical model



Karato (2011)

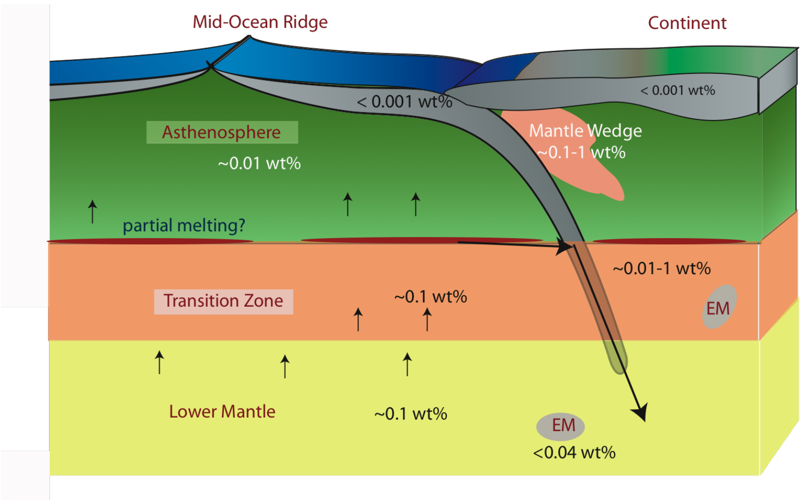


Karato (2011)

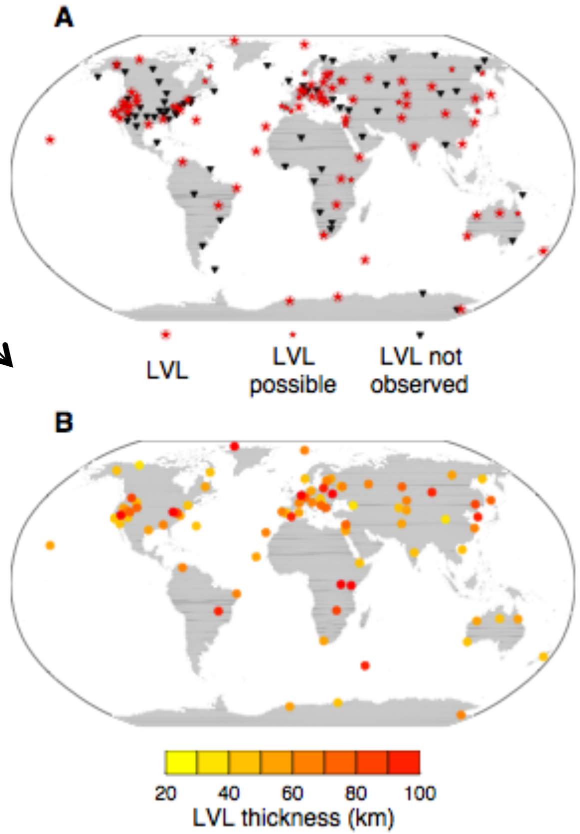
"Plum pudding" model is not consistent with observed electrical conductivity.

Inferred layered water distribution suggests **mid-mantle melting**.

- Evidence for 410-km melting
  - Low velocity layer
  - Water content layering

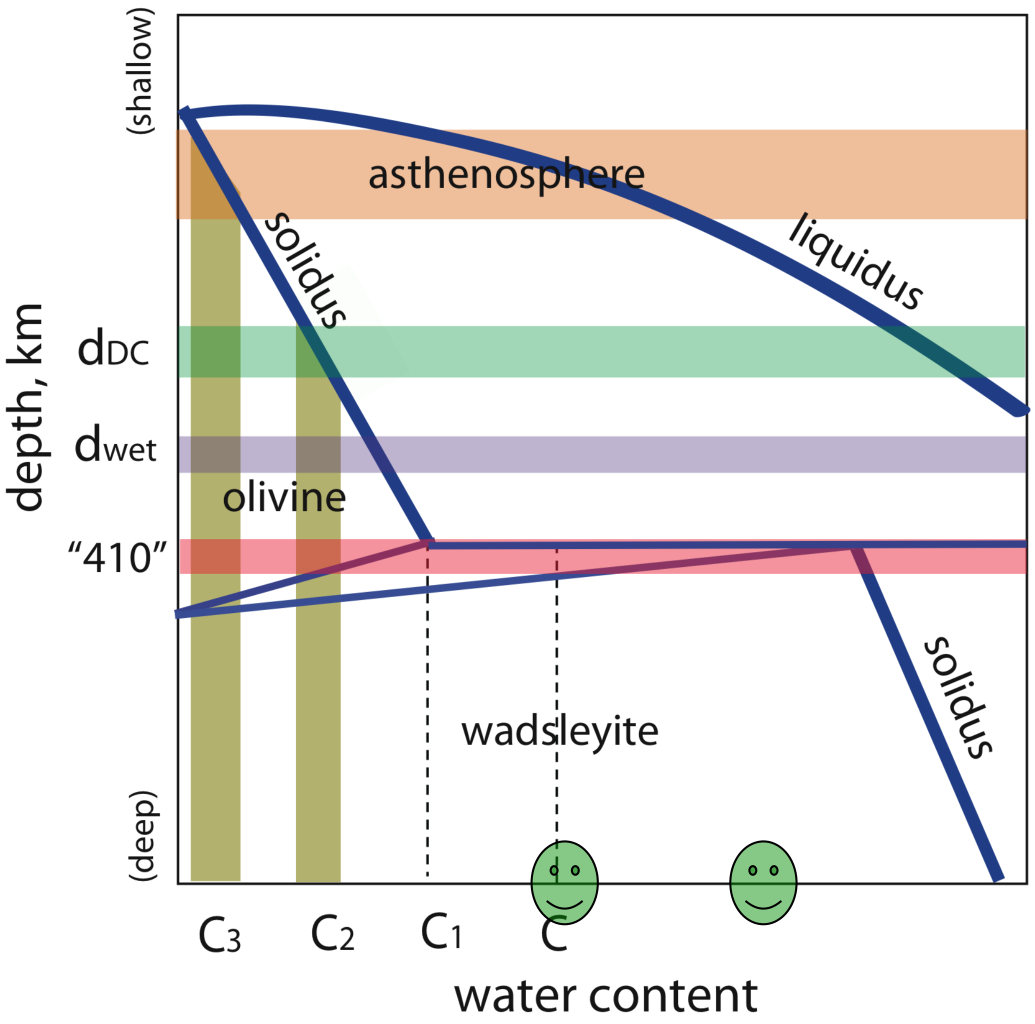


Karato (2011)



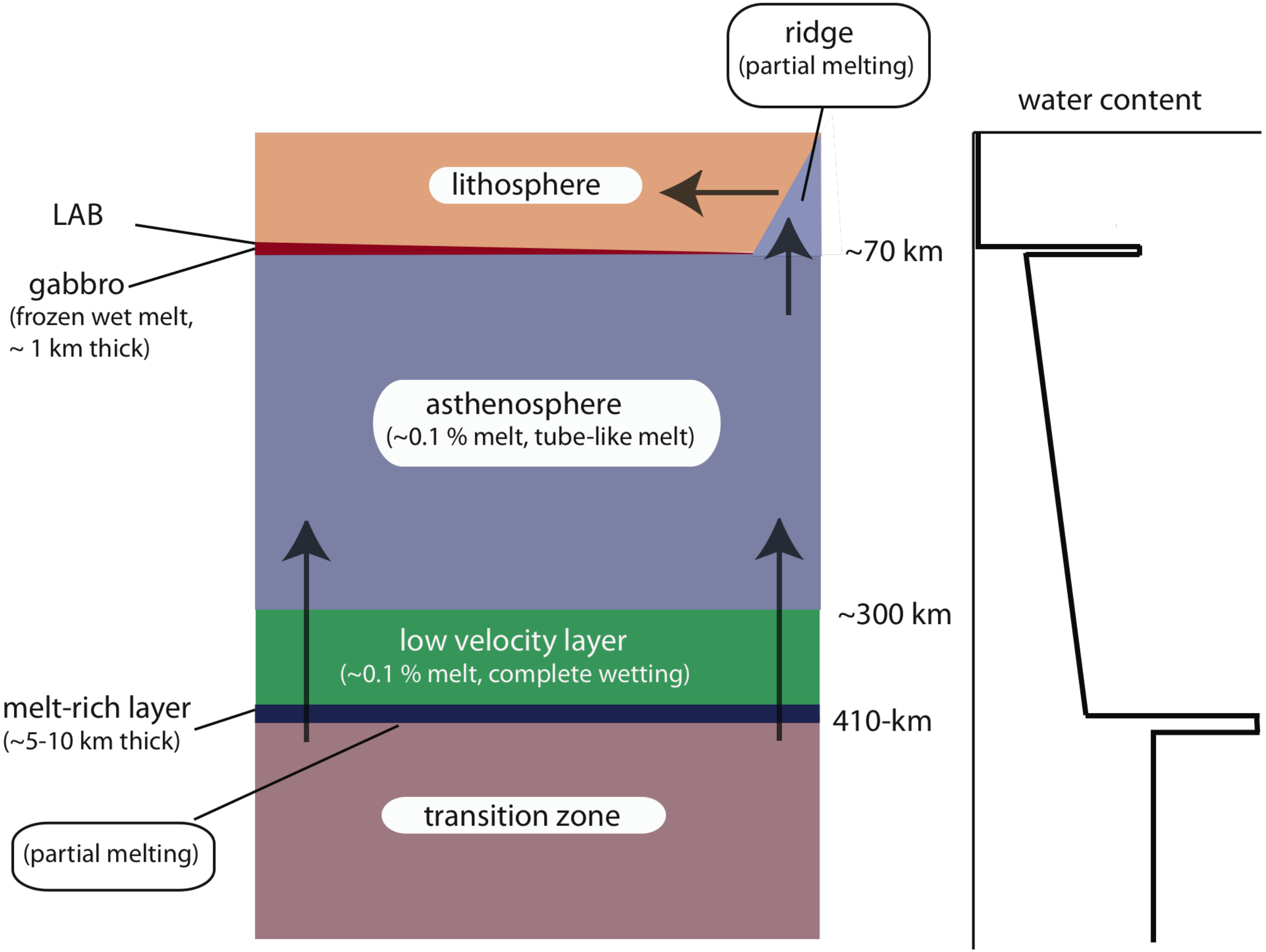
Tauzin et al. (2010)

What happens after 410-km partial melting?



- Partial melting (at 410km) homogenizes the composition of residual solids → water content in the upper mantle is constant → stabilizes the degassing rate

Karato (2011)


ridge
(partial melting)
water content
lithosphere
LAB
~70 km
gabbro
(frozen wet melt,
~ 1 km thick)
asthenosphere
(~0.1 % melt, tube-like melt)
~300 km
low velocity layer
(~0.1 % melt, complete wetting)
melt-rich layer
(~5-10 km thick)
410-km
transition zone
(partial melting)

Karato (2011)

$$\frac{dX^{ocean}}{dt} = \frac{1}{\tau_1} X^{mantle} - R = \frac{1}{\tau_1}\left(X^{total} - X^{ocean}\right) - R$$

$$\frac{dX^{mantle}}{dt} = -\frac{1}{\tau_1} X^{mantle} + R$$

→ $\bar{X}^{ocean} = X^{total} - \tau_1 R$: ocean mass is sensitive to regassing rate

$$\frac{dX^{ocean}}{dt} = \frac{X^{UM}}{\tau_1} + \frac{X^{MTZ}}{\tau_2} - R$$

$$\frac{dX^{UM}}{dt} = -\frac{X^{UM}}{\tau_1} + \beta R + Y$$

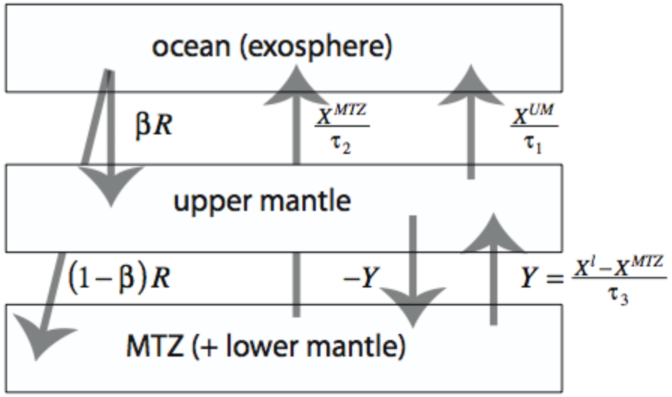
$$\frac{dX^{MTZ}}{dt} = -\frac{X^{MTZ}}{\tau_2} + (1-\beta)R - Y$$

→ $\bar{X}^{ocean} = X^{total} - \xi\tau_1 R - \zeta X^l$

with $\xi = 1 - \frac{\tau_3}{\tau_1}\frac{\tau_2-\tau_1}{\tau_2-\tau_3}(1-\beta)$ and $\zeta = \frac{\tau_2-\tau_1}{\tau_2-\tau_3}$

if $\zeta = \frac{\tau_2-\tau_1}{\tau_2-\tau_3} > 0$, then $\xi < 1$

→ ocean mass is less sensitive to regassing rate



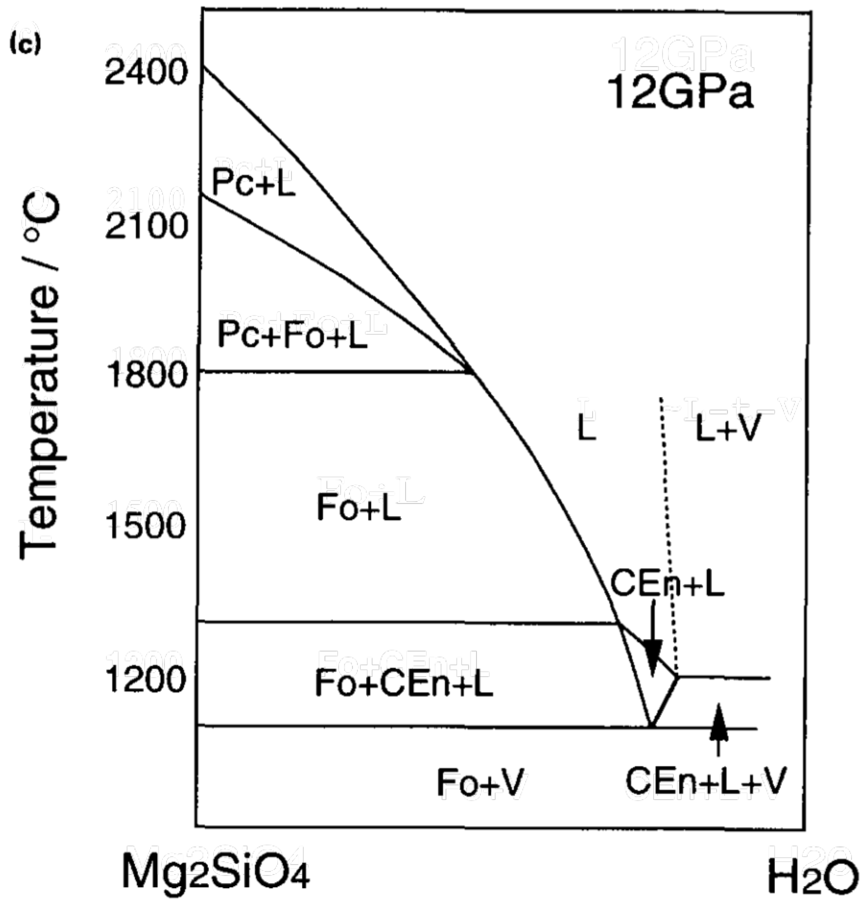
Karato (2011)

Deep mantle melting buffers (stabilizes) the ocean mass.

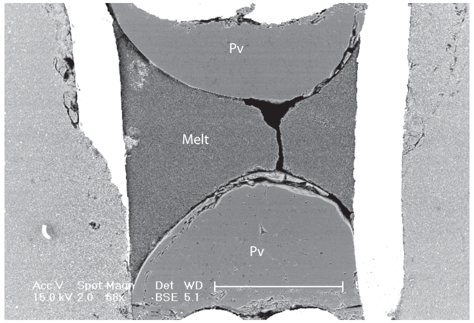
Water has strong effects on the melting under the deep mantle conditions

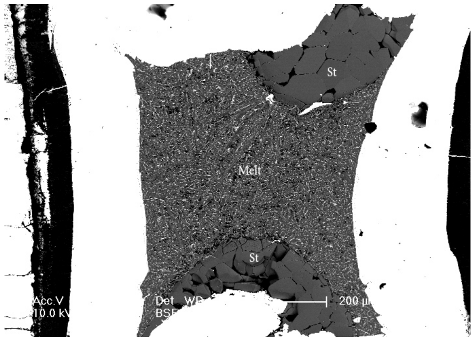
- Addition of water **reduces the solidus** of the lower mantle assembly by more than ~1500 K
- Addition of water changes the composition of melts and the residual: **highly ultramafic melts + silica-rich residual**

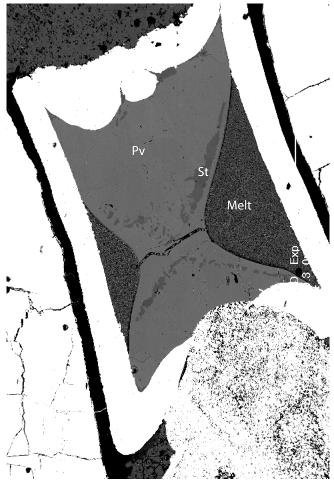
→ Geochemical evolution of Earth



Inoue et al. (1994)







Melting occurs in the perovskite-rich system (+ water) at 25 GPa and 1500 C (without water, one would need ~3000 C for melting). Melt is (Mg,Fe)O rich → **heavy melt.** Residual solid is SiO_2 rich.

conclusions

- Water distribution in the planetary interior can be mapped from geophysical observations.
- **Electrical conductivity**

  highly sensitive to water content, insensitive to other variables

  (**seismological observations** - insensitive to water, non-sensible results)
- **Mantle water content in Earth's mantle is layered.**
  - ~0.01 wt% for the upper mantle, ~0.1 wt% for the transition zone

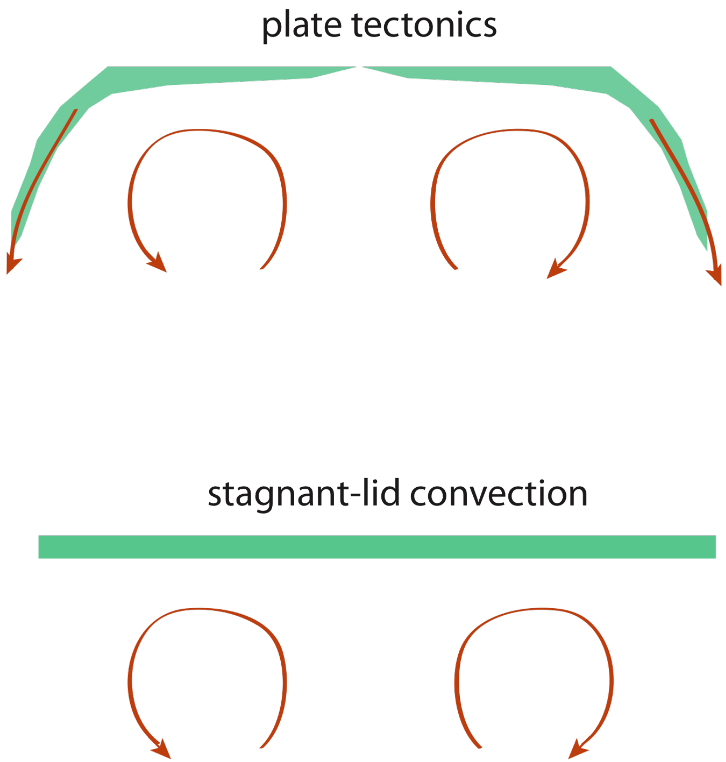
  → **partial melting at 410-km**?
- **Ocean mass may be buffered by the partial melting at 410-km**
- **Melting could also occur below 660 km → (Mg,Fe)O-rich (dense) melt.**

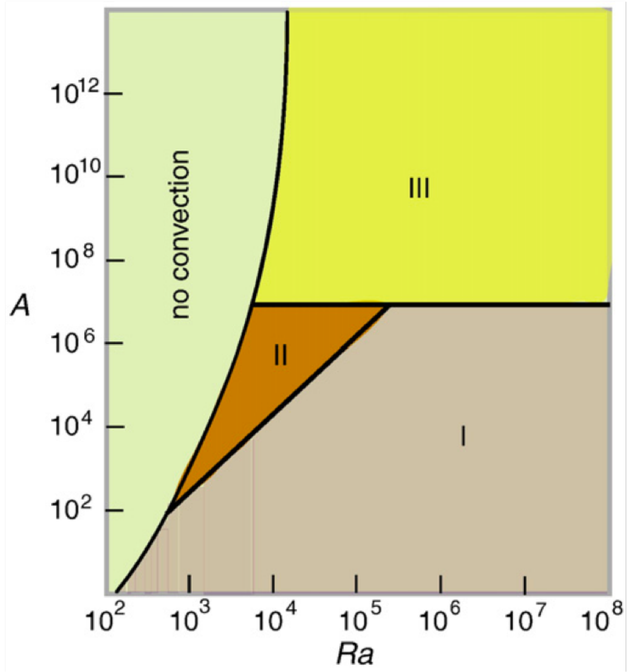
Plate tectonics (mode of mantle convection)

- Plate tectonics provides an efficient way to circulate volatiles (→ stabilizes the surface ocean?).
- Plate tectonics is not an obvious mode of mantle convection: Plates may be too strong to be involved in convection ("stagnant lid").
- Does plate tectonics occur in other terrestrial planets (e.g., super-Earths)?

Modes of convection

(Influence of near-surface layer: **T-effect**, water effect)





Solomatov and Moresi (1997)

Classification using **a two-parameter model**

Plate tectonics occurs when the near surface layer is modestly strong (<200 MPa (for Earth))

If the plate is too strong → "stagnant lid" convection

Plate tectonics versus stagnant-lid convection

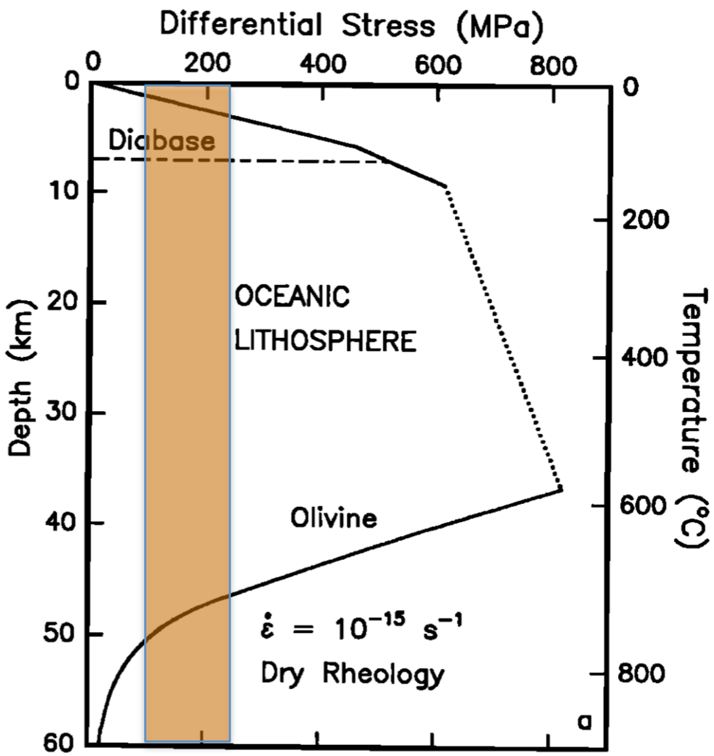
- [driving force (gravitational energy release)] ←→ [resistance for convection (energy dissipation due to deformation)] = [plate deformation] **or** [stagnant lid (convection below the lid))]

strong plate → stagnant-lid convection

weak plate → plate tectonics

[critical strength ~100-200 MPa (for Earth)]

Is the lithosphere of Earth weak enough for plate tectonics?

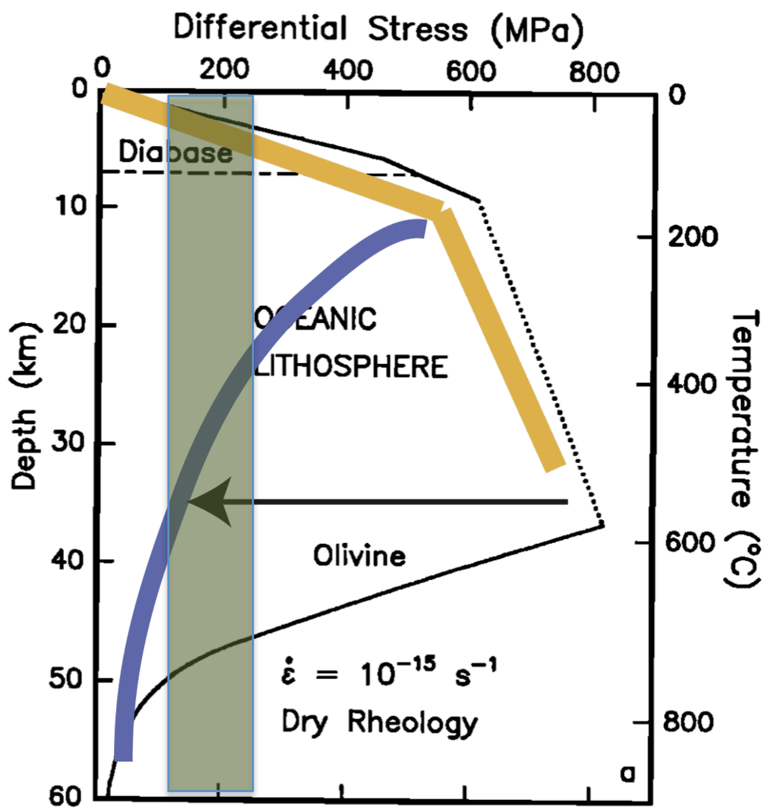


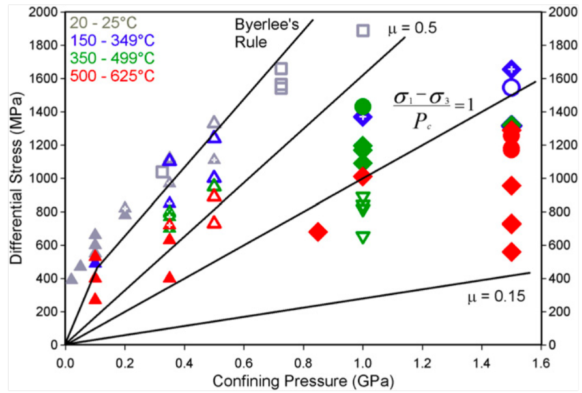
- For Earth, the simplest model predicts too high strength for plate tectonics
  - "water" effects?
  - shear localization (grain-size)?
- How about on other planets?

Kohlstedt et al. (1995)

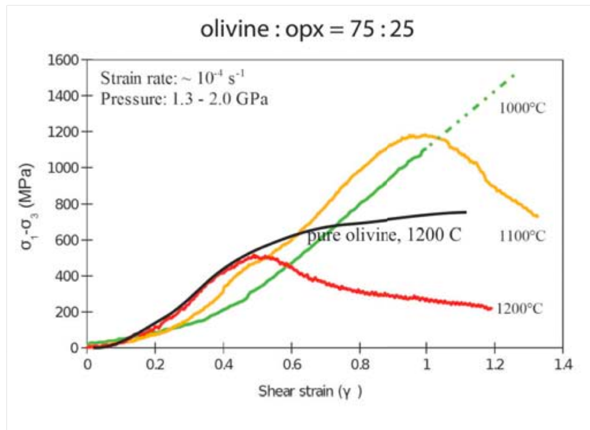
How to weaken the lithosphere?

Brittle ←→ Ductile





friction: Chernak-Hirth (2010)



flow: Farla et al. (2012, submitted)

Weakening in the brittle regime is limited, but **weakening in the ductile regime can be large**.

How about other planets?

- Size (mass)
- Water
- Surface temperature

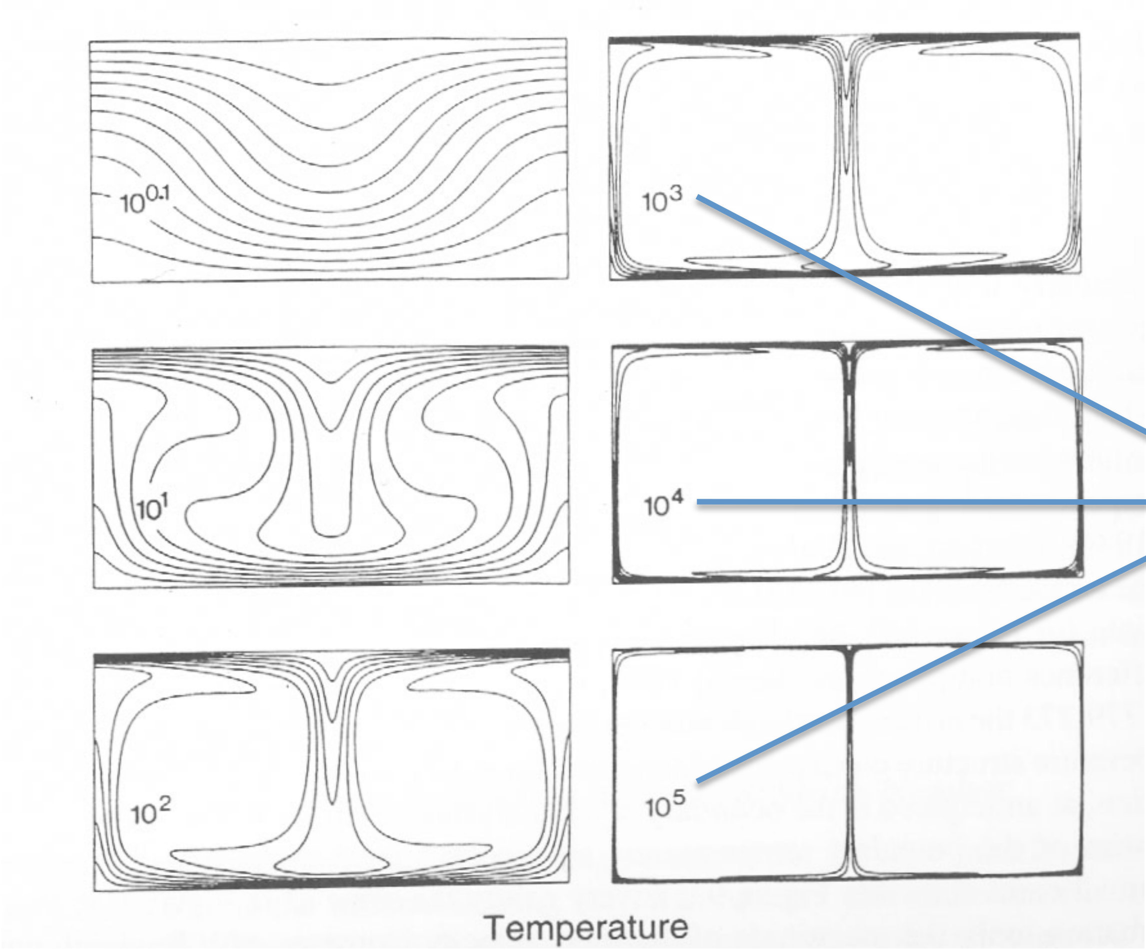
How do these factors affect [driving force] and [resistance for plate subduction] in other planets?

→ Basics of convection (boundary layer theory)

→ Strength of plates

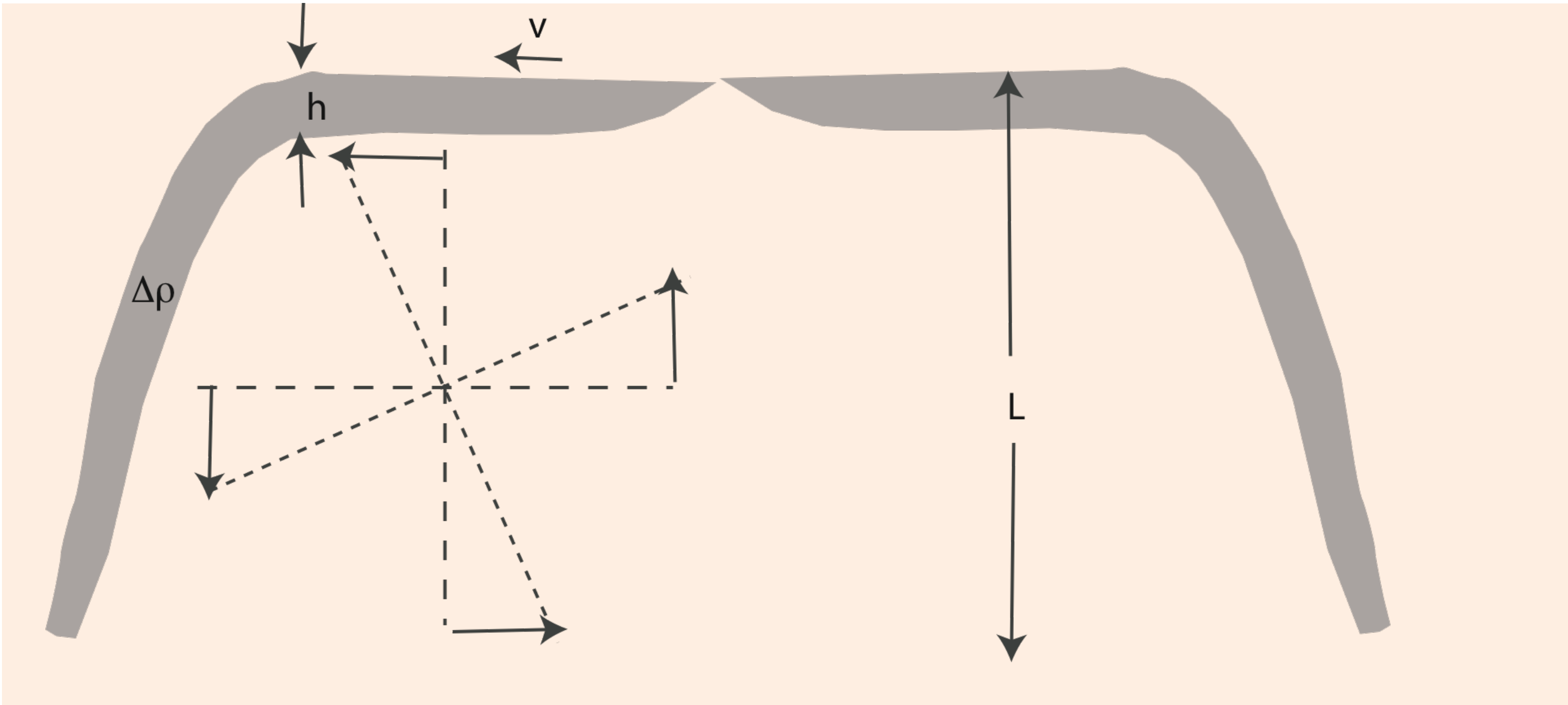
A boundary layer model of convection

When the fluid layer is highly unstable, the temperature-gradient and deformation are localized in thin “boundary layers”.



$$Ra = \frac{\alpha \rho g L^3 \Delta T}{\eta \kappa}$$

$$Ra / (Ra)_c$$


v
h
Δρ
L

$$F_{drive} = h\Delta T \cdot \rho \alpha g$$

$$F_{resist} = \eta \frac{\partial \upsilon}{\partial x} \approx \eta \frac{\upsilon}{L/2}$$

$$F_{resist} = F_{drive} \rightarrow h = \frac{2\eta\upsilon}{L\Delta T \cdot \rho\alpha g} \qquad (1)$$

now, plate thickness (h) is determined by plate cooling

$$\rightarrow h \approx 2\sqrt{\kappa t} = 2\sqrt{\kappa L / \upsilon} \qquad (2)$$

eliminating v from (1) and (2),

$$\frac{h}{L} = 2\left(\frac{\eta\kappa}{L^3 \rho\alpha g \Delta T}\right)^{\frac{1}{3}} = 2Ra^{-\frac{1}{3}} \qquad (3)$$

$$\upsilon = \frac{1}{4}\frac{\kappa}{L} Ra^{\frac{2}{3}} \qquad (4)$$

$$Ra = \frac{\alpha\rho g L^3 \Delta T}{\eta\kappa}$$

heat flux

$$J = k\frac{\Delta T}{h} = J_o Nu \quad (J_o = k\frac{\Delta T}{L})$$ (Nu: Nusselt number)

$$\rightarrow Nu = \frac{L}{h} = \frac{1}{2} Ra^{\frac{1}{3}} \qquad (5)$$

Turcotte and Oxburgh (1967)

$$Ra = \frac{\alpha \rho g L^3 \Delta T}{\eta \kappa}$$

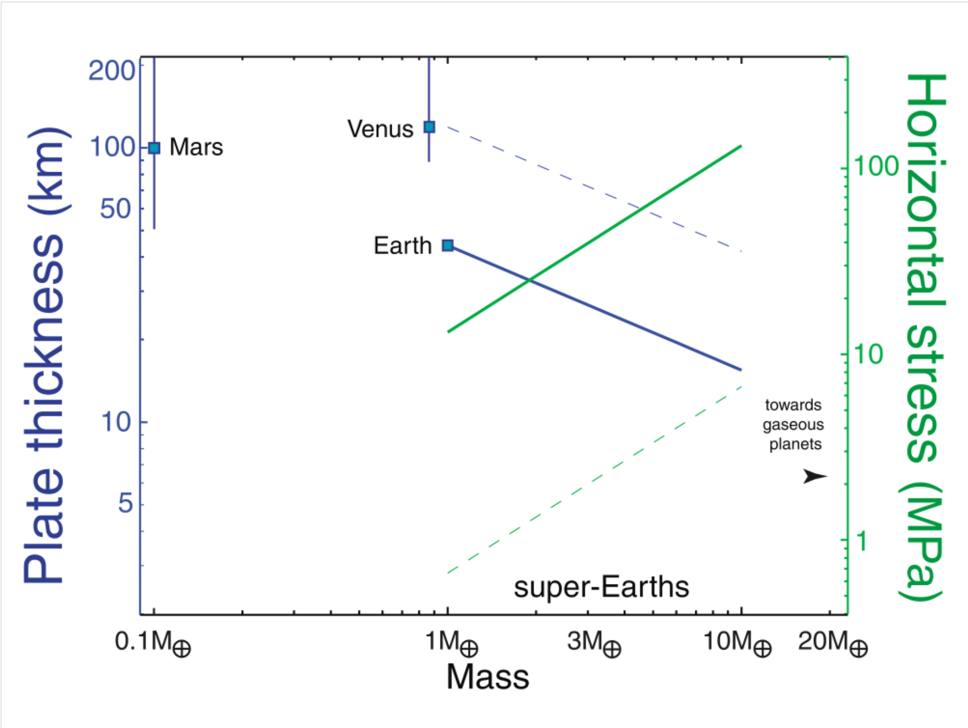
- If viscosity is not strongly dependent on planetary mass, *Ra* increases with planetary mass.

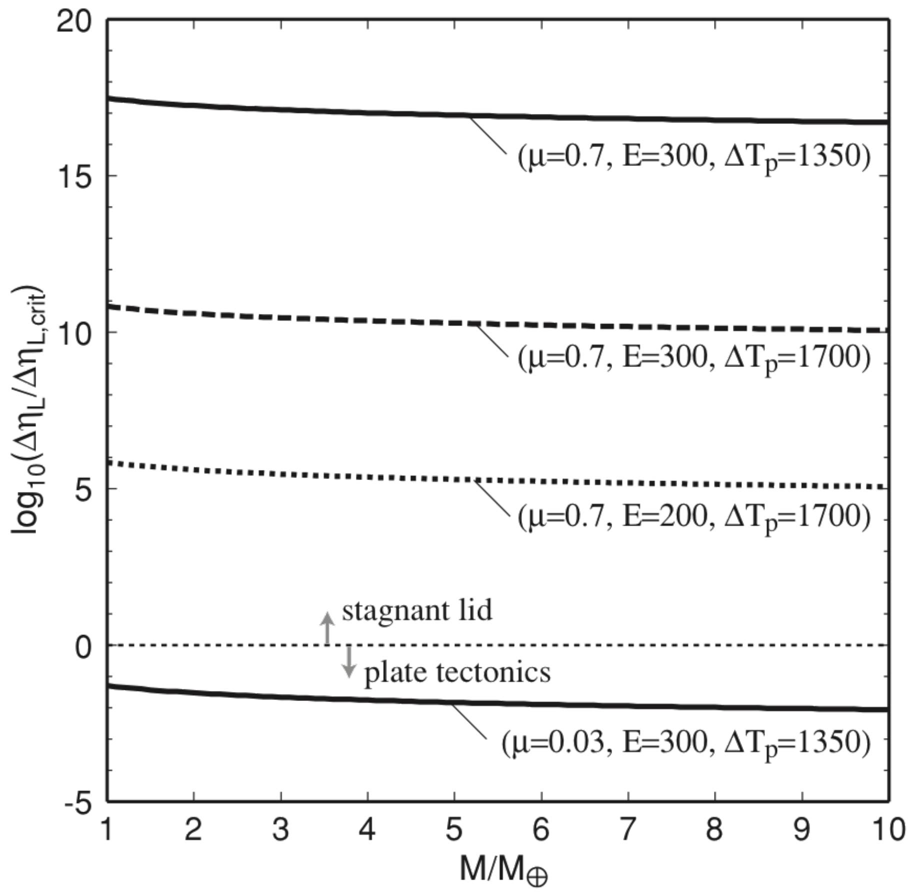
→ large planet → large driving force + thin plate

→ easy for plate tectonics to operate

- But viscosity (average viscosity) may strongly depend on planetary size---- .
- Also plate strength may depend on “other parameters”.

- Both the driving force and the resistant to plate deformation depends on **Rayleigh number** + **strength** (plate strength, mantle viscosity)
- Both Rayleigh number and strength depend on **planetary size** + **something else**.
- **Something else**
  - water (e.g., Regenauer-Lieb (2006), Korenaga (2010))
  - grain-size [surface temperature] (e.g., Landuyt-Bercovici (2009), Foley-Bercovici (2012))





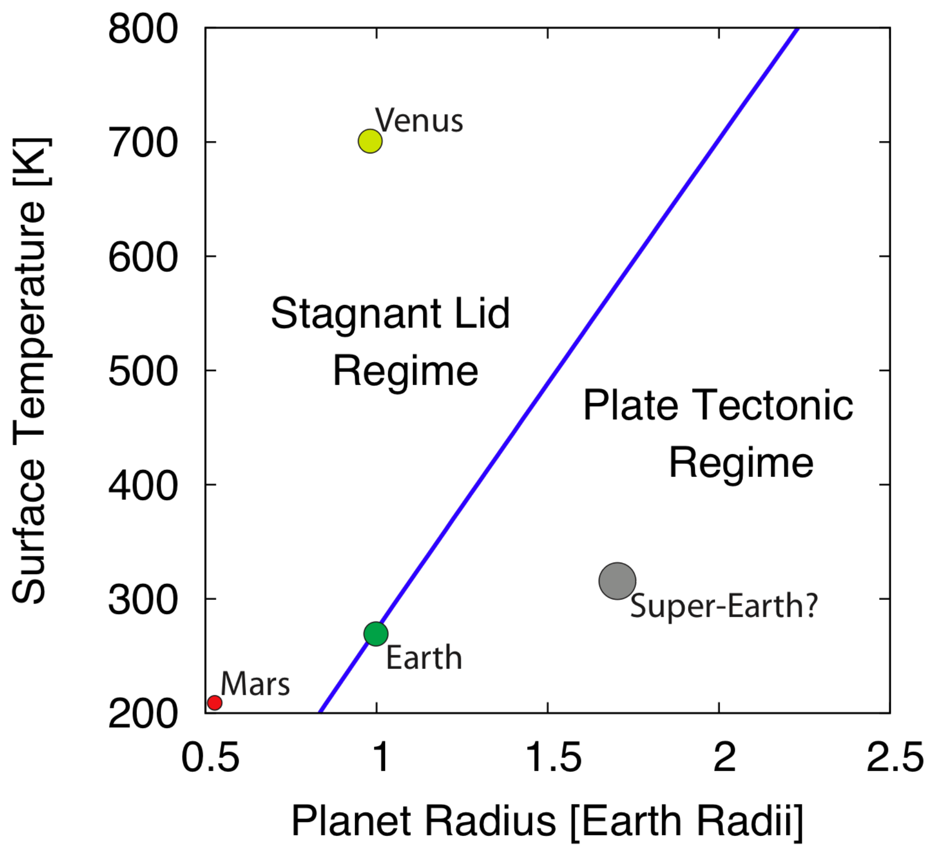
Valencia-O'Connell (2007):

Planetary mass is most important

→ large mass → high Rayleigh number

→ large driving force + thin plate

Korenaga (2010) : **friction coefficient** (strength of lithosphere) is most important, the planetary mass is NOT important



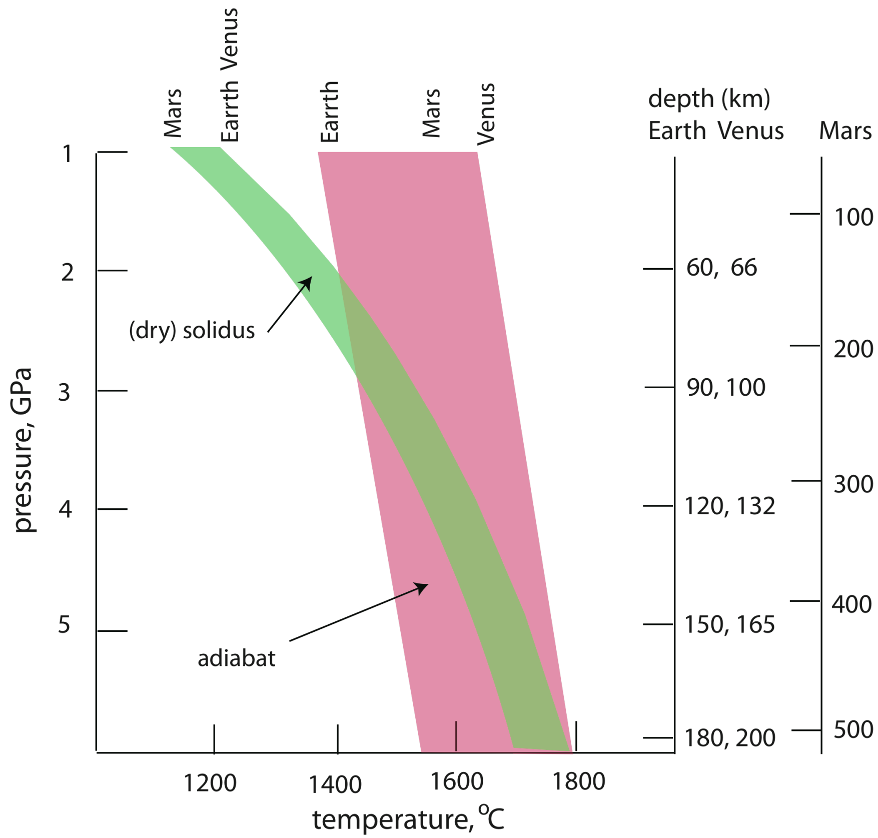
Foley-Bercovici (2012):

Plate strength is controlled by **grain-size reduction**. Driving force increases with planet size.
Grain-size reduction depends on (near surface) temperature through grain-growth.
Both planet size and surface temperature are important.

Limitations of the previous studies

- For the **driving force**, **pressure dependence of viscosity** has been ignored in all previous studies (mass → P, large effects).
- For the **resistance force**, conditions for plate failure (deformation) are not well understood (essence of **mineral physics of strength reduction** has not been incorporated in the previous large-scale models).

Doesn’t planetary size matter? (1)



Planetary size (mass) changes plate thickness **(small planet → thick plate).**

Lithosphere thickness determined by dehydration-hardening (Karato (1986), Hirth-Kohlstedt (1996)) depends on planetary size (due to gravity): lithosphere will be thicker for a smaller planet

Doesn't planetary size matter? (2)

Planetary size could change the **driving force** through the P-dependence of viscosity

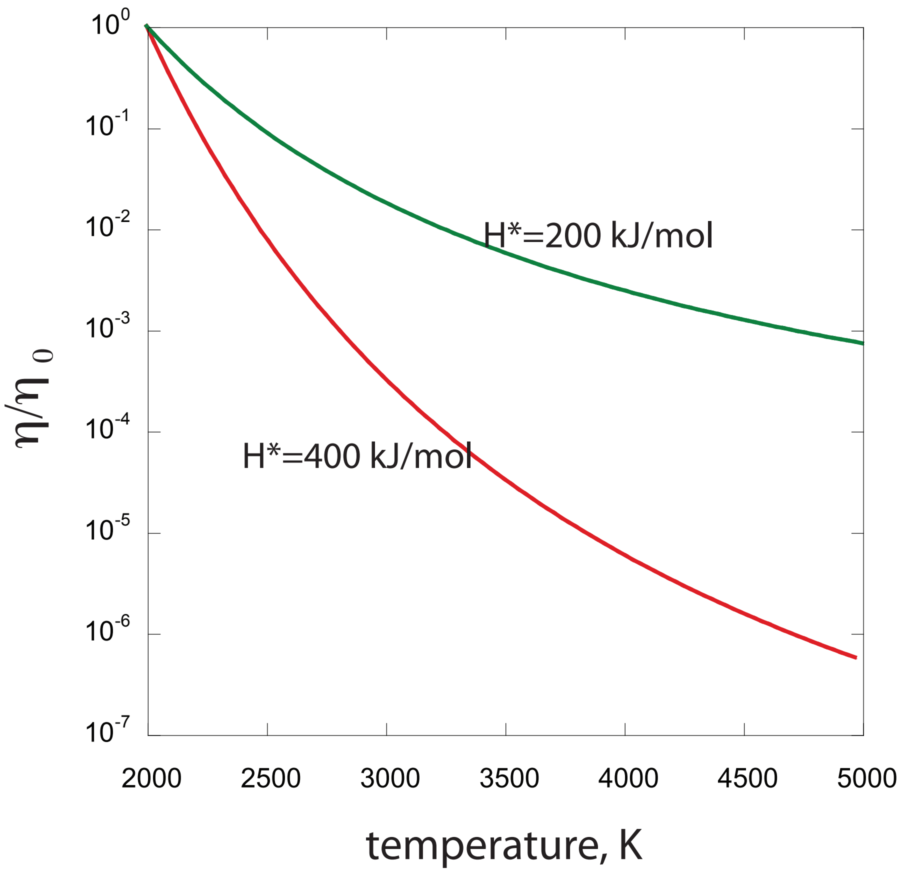
- Rayleigh number (partly) controls the plate thickness and vigor of convection
- Rayleigh number depends on viscosity
- Viscosity changes with T and P (and water content ---)
  - But P-effect was ignored---.

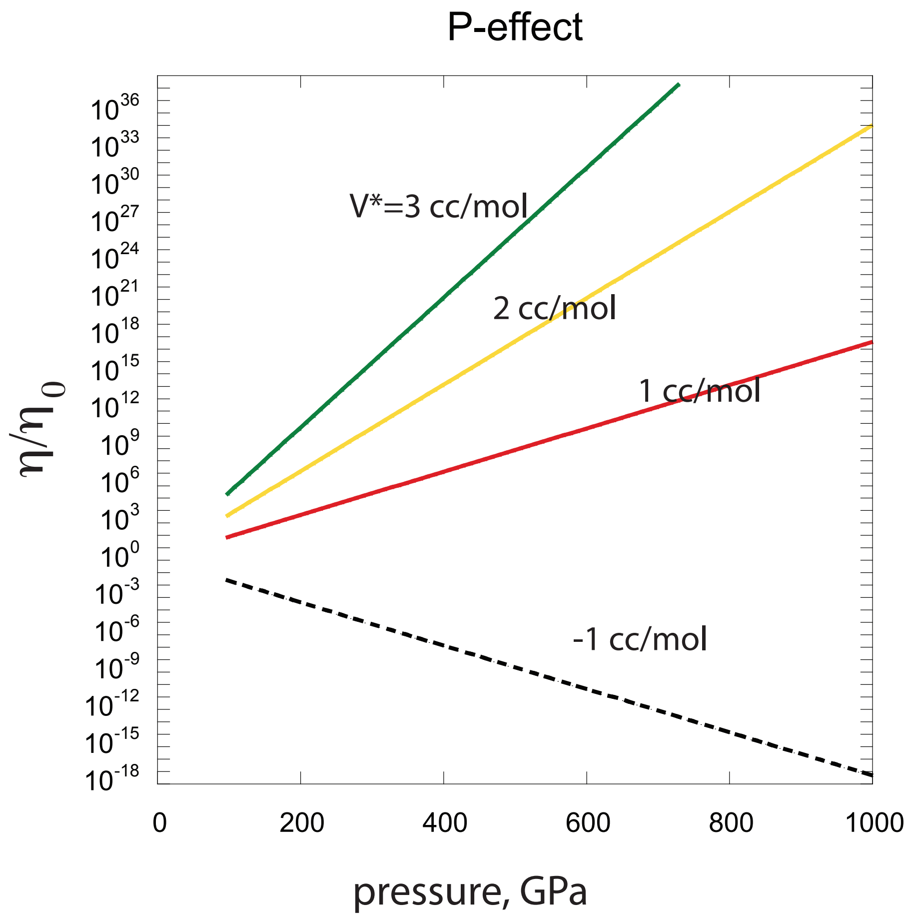
$$Ra = \frac{\rho \alpha g \Delta T L^3}{\eta(T, P) \cdot \kappa}$$

Viscosity of planetary materials depends strongly on T and P.

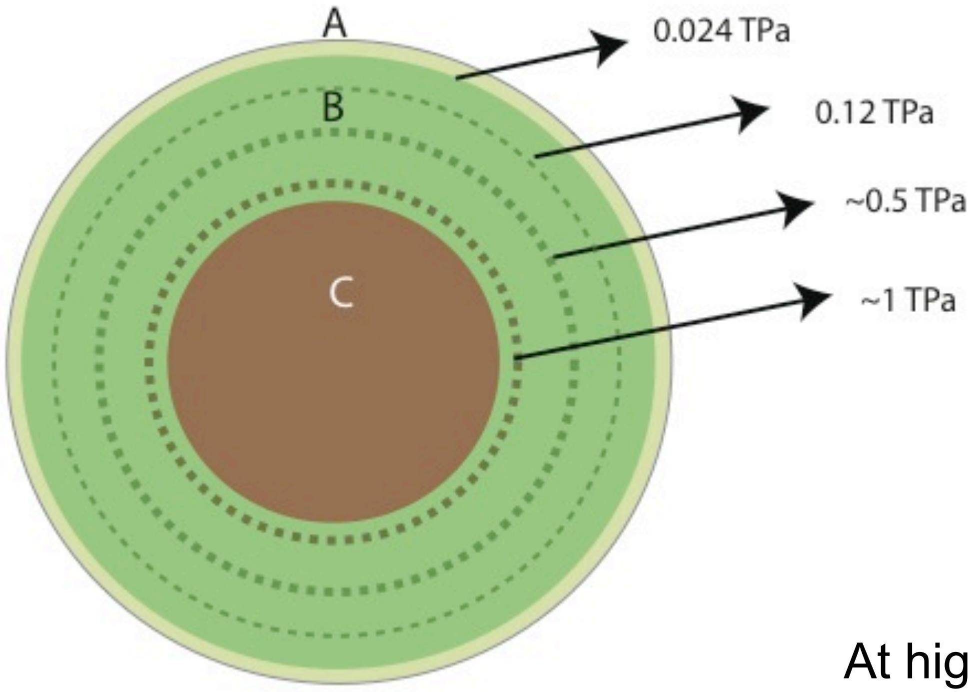
P-effect is potentially very large!

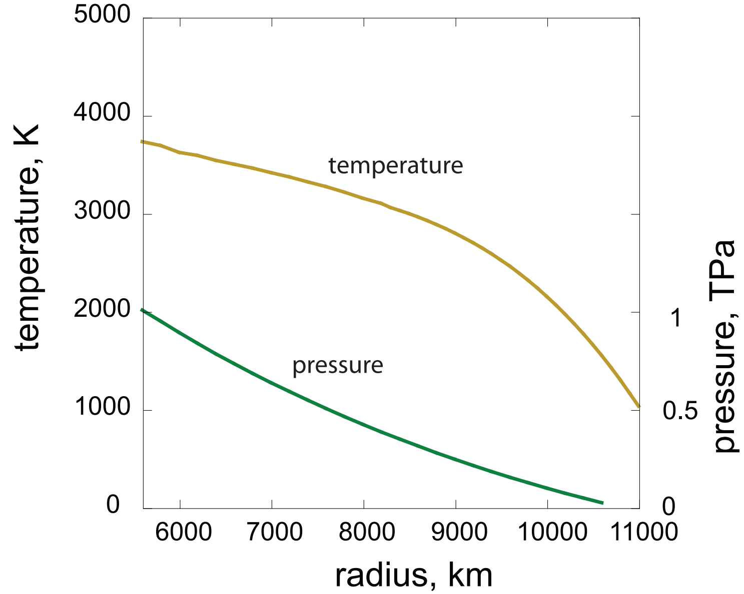
$$\eta = \eta_0 \exp\left(\frac{E^* + PV^*}{RT}\right) = \eta_0 \exp\left(\frac{H^*}{RT}\right)$$





Internal structure of a super-Earth

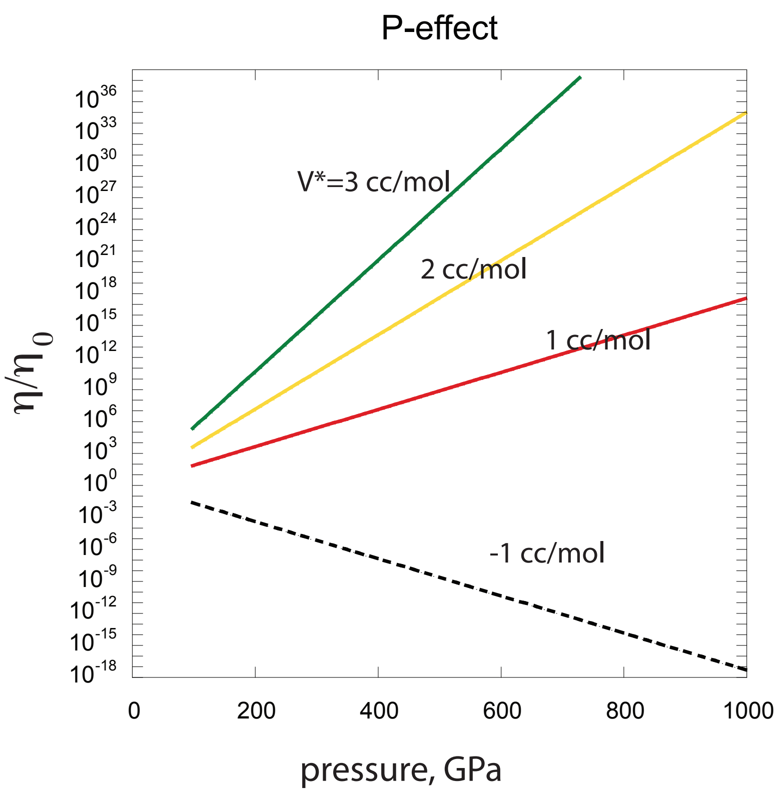


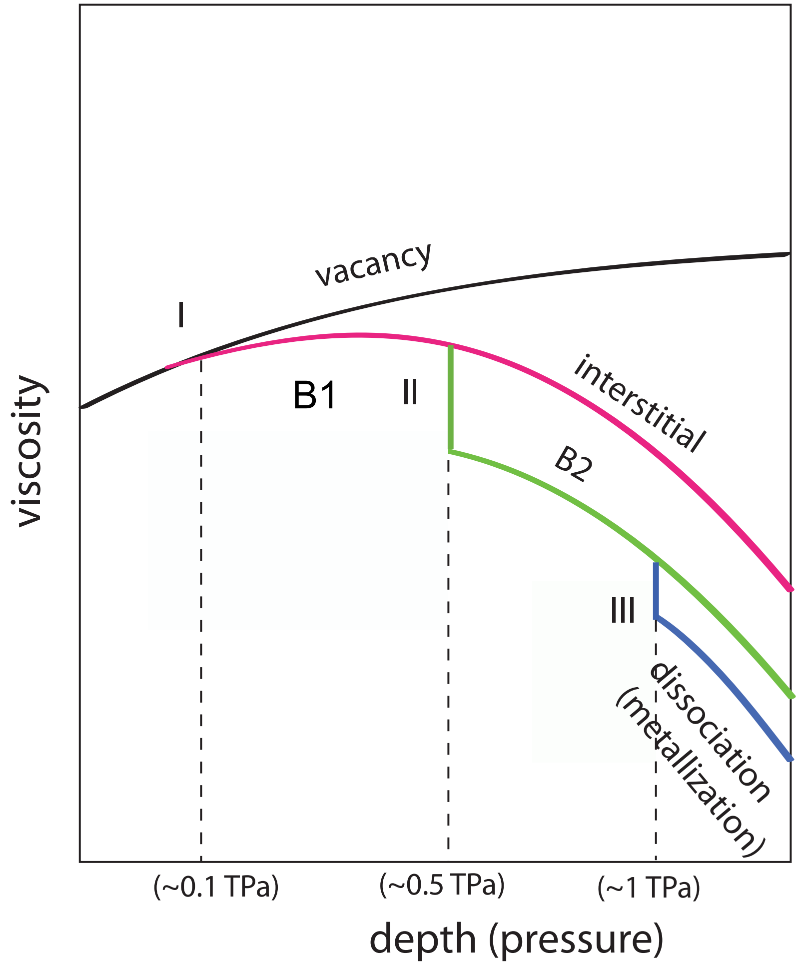


P to ~ 1 TPa (1000 GPa)
T to ~5000 K

At high P (~1 TPa)
(1) B1→ B2 transition
(2) Mechanism change of diffusion
(3) dissociation of post-perovskite
(4) metallization?

Viscosity of solids increases with P at low P.
Is this valid at higher P in super-Earths?





Karato (2011)

Viscosity-mass relationship

(T-viscosity interaction (self-regulation): Tozer effect)

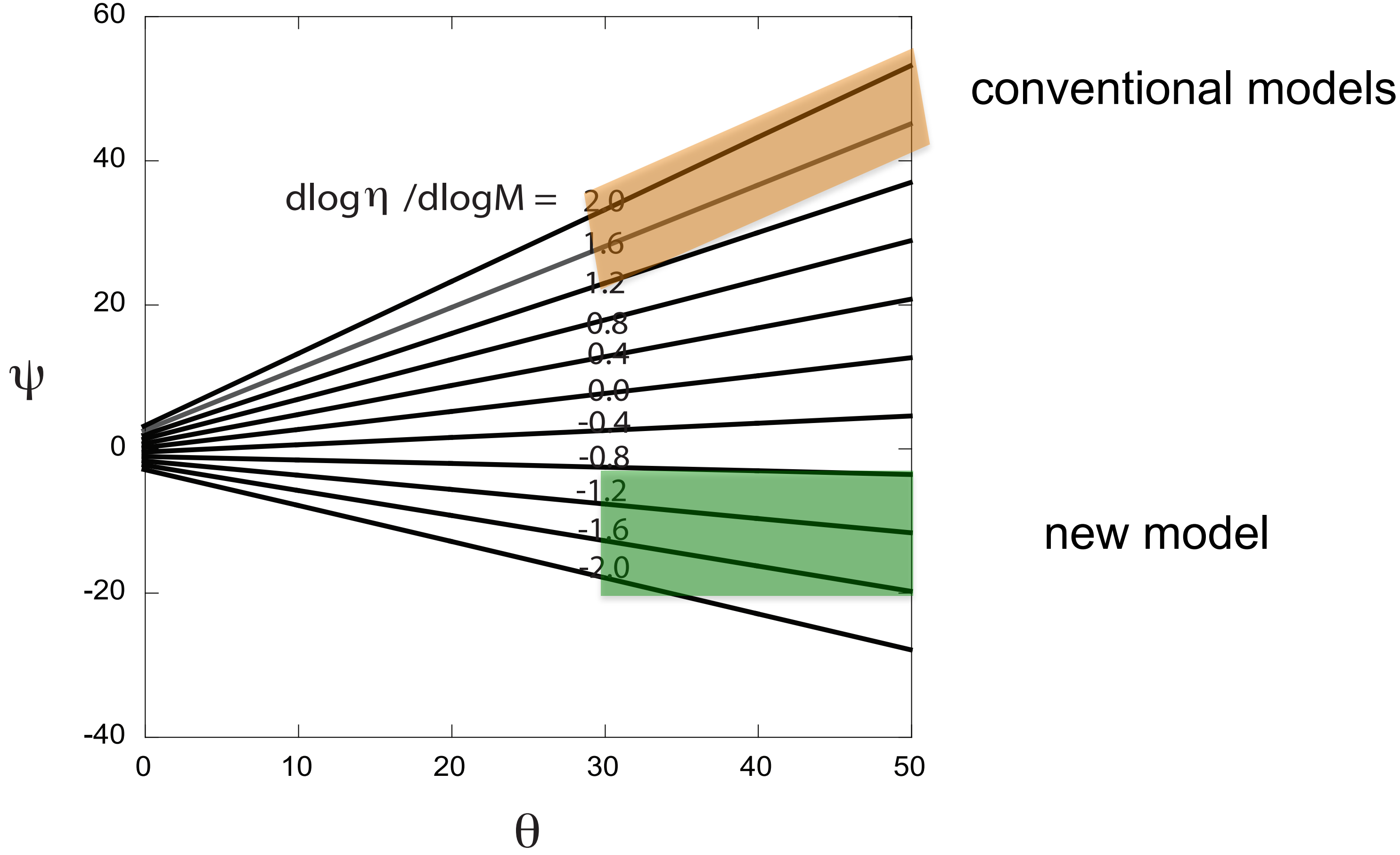
$$M \cdot Heat = A \cdot Nu \cdot \frac{k(T - T_s)}{d}$$ (energy balance ← T-η feedback)

$$Nu = \left(\frac{\rho g \alpha (T - T_s) d^3}{\kappa \eta} \right)^{\beta}, \qquad \eta \propto T^{-\theta} P^{\psi}$$

→ $T \propto M^{\frac{2-4\beta+2\psi\beta}{3(1+\beta+\theta\beta)}}$ and $\eta \propto M^{-\frac{(2-4\beta+2\psi\beta)}{3(1+\beta+\theta\beta)}+\frac{2}{3}\psi} \approx M^{-\frac{2}{3}+\frac{8}{3}\frac{\psi}{\theta}}$

→ **Pressure dependence of viscosity will change the η-M relation**

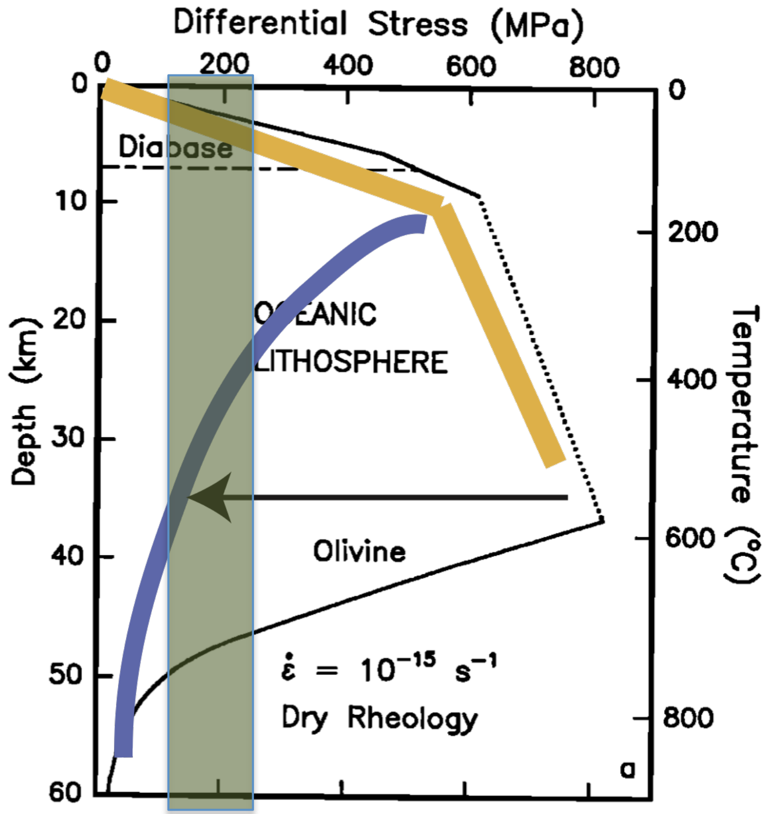
$$\eta \propto T^{-\theta} P^{\psi}$$

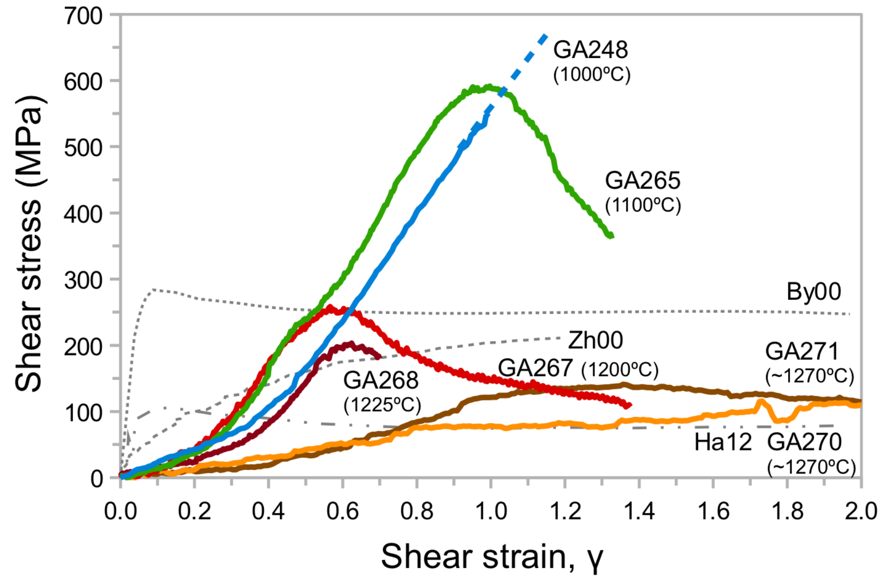


Karato (2011)

How to weaken the lithosphere?

Brittle ←→ Ductile





Farla et al. (2012, submitted)

Weakening in the brittle regime is limited, but weakening in the ductile regime can be large.
Weakening in the ductile regime depends on T and water content.

Conclusions

- In order to assess if **Plate Tectonics** occurs on other planets (e.g., super-Earths), we need to know what controls the magnitude of **driving force** and the **resistance for plate deformation.**

- **Major remaining issues**:
  Physical mechanisms of **localized deformation**
  Dependence of viscosity on **pressure** (phase transformations)

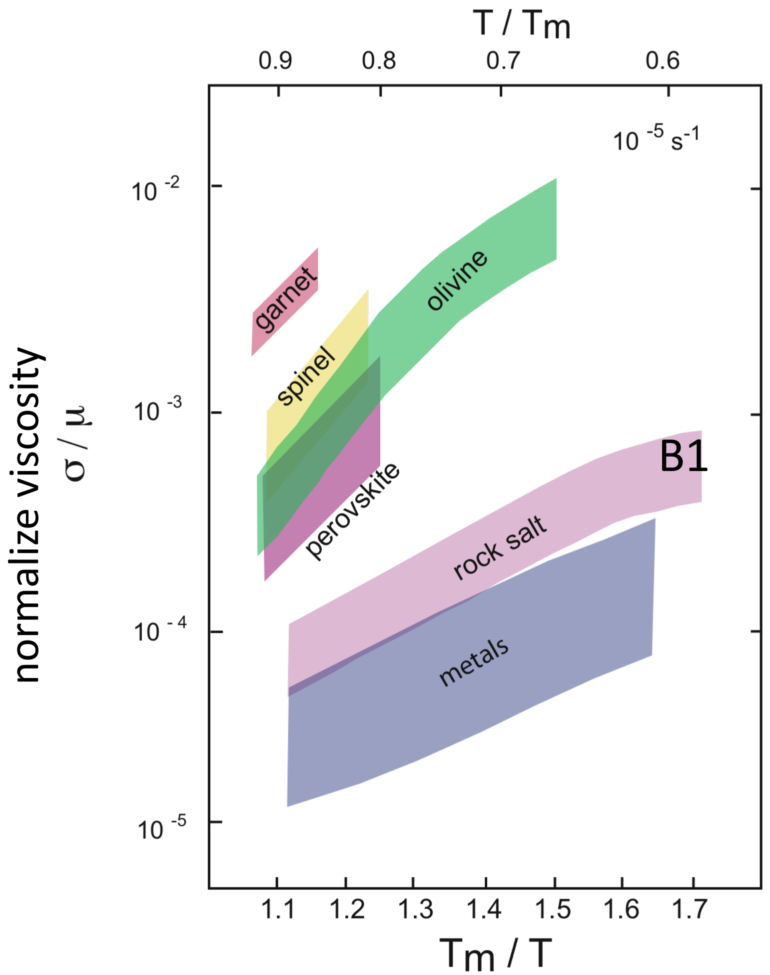
Summary

- **Volatile acquisition during planetary formation**
  - early or late acquisition? (→ H in the core?)
    - geochemical observations
  - liquid phases control volatile acquisition
    - volatility ←→ affinity to liquids (to Fe etc.)
- **Volatile circulation in a planet**

  (longevity of the surface ocean)
  - The role of deep (mid-) mantle melting
  - Plate tectonics on other planets?
    - "rheological properties"
      - shear localization, deep mantle viscosity

Viscosity changes also with crystal structure/ chemical bonding.

normalized temperature



In most of super-Earth's mantle, MgO is the softest phase.
MgO changes its structure from B1 to B2 at ~0.5 TPa. B2 structure is softer than B1 structure.

(modified from Karato (1989))

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